UCRL-MI-231268

IFE Science and Technology Strategic Planning Workshop - Part 1: April 24, 2007 Presentations

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IFE Science & Technology — **Strategic Planning Workshop**

San Ramon, California — April 24-27 2007

Technical Program

Day 1, Tuesday, April 24

Overviews - Approaches to IFE

7:00-8:00 Registration and Continental Breakfast

All Day Plenary Session

8:00-8:30 Workshop Motivation and Objectives (Ed Synakowski, LLNL)
8:30-9:00 Setting the Stage for IFE and Workshop Overview (Wayne Meier, LLNL)

Following speakers to address current status, near-term plans, long-range visions and funding needs to move to the next step for the particular approach. With respect to planning, address

- How do you see your approach evolving beyond the near term?
- What needs to be accomplished to move forward on such a strategy?
- What are the potential landscape-changing developments?
- What are the technical issues for your approach?

9:00-9:30 HAPL/KrF (John Sethian, NRL)
9:30-9:40 Q&A

9:40-10:00 Break

10:00-10:30 DPSSL (Al Erlandson, LLNL)
10:30-11:00 Discussion

11:00-11:30 FTF (Steve Obenschain, NRL)
11:30-12:00 Discussion

12:00-1:00 Lunch

1:00-1:30 HIF (Grant Logan, LBNL)
1:30-2:00 Discussion

2:00-2:30 Z-IFE (Craig Olson, SNL)
2:30-3:00 Discussion

3:00-3:15 Break

3:15-3:45 FI as a Cross-Cutting Option for IFE (Mike Campbell, GA)
3:45-4:00 Discussion

4:00-4:30 The Potential Benefits of Magnetic Fields in Inertially Confined Plasmas (Bruno Bauer, UNR)
4:30-4:45 Discussion

4:45-6:00 Panel Discussion (M. Campbell, S. Dean, G. Logan, C. Olson, C. Sangster, J. Sethian, E. Synakowski) What can/should we do to be prepared to take advantage of growing interest in and funding for IFE that could be triggered by a variety of events (e.g., successful ignition on NIF, increase concern about global climate change, increase interest in domestic energy sources, etc.)?

Day 2, Wednesday, April 25

Working Together in the Near-Term to Advance IFE and Related Science

7:30-8:00 Continental Breakfast

Interagency Approach to High Energy Density Laboratory Plasmas (HEDLP)
8:00-8:20 Overview of the National Task Force Report on HEDP: Setting the Stage (Ron Davidson, PPPL)
8:20-8:50 OFES, NNSA Perspectives (Ray Fonck, OFES; and Chris Keane, NNSA)
8:50-9:15 Updated Planning for HED-LP (Francis Thio, OFES)
9:15-9:45 Discussions

9:45-10:00 Break

Plenary Talks: Existing and near-term ICF/HEDP capabilities and research plans focusing on R&D relevant to IFE
Questions to focus the plenary talks include:
- What are the HEDP questions that can be addressed in the near-term that are relevant to IFE? How can NNSA facilities be used to support IFE both now and post ignition?
- What are current or planned interactions with the other communities (ICF/HEDP/IFE)?
- Who are the customers for this HEDP science besides the IFE/ICF community?

ICF/HEDP Facilities and R&D:
10:00-10:45 NIC and NIF (John Lindl, LLNL)
10:45-11:15 Omega (John Soures, UR-LLE)
11:15-11:45 Z-pinch (Keith Matzen, SNL)
11:45-12:15 Nike--1) ICF Experiments and Plans, 2) ICF Physics Issues (Andy Schmitt, NRL)

12:15-1:15 Lunch

1:15-1:45 Advanced Ignition (Fast and other two-step ignition) (Riccardo Betti, UR-LLE)
1:45-2:15 HIFS/WDM/Hydrodynamics Experiments on NDCX-I and NDCX-II (John Barnard, LLNL)
2:15-2:45 A Pathway to HEDP: Magnetized Target Fusion (Glen Wurden, LANL)

2:45-3:00 Break

3:00-5:00 PM - Breakout Session - Working Together to Advance IFE and Related Science*
Four groups. Same questions for each group:
- What are the HEDP questions that can be addressed in IFE-relevant NNSA and OFES facilities? Which questions are directly relevant to IFE? What types of IFE relevant experiments can be done on NNSA ICF facilities?
- How does addressing these questions enable progress in IFE?
- What opportunities exist that can be captured with growing budgets?
- How are the IFE/ICF/HEDP communities working together to maximize use of limited resources to advance the underlying science of IFE? What obstacles exist? How can these working relationships be improved?

***Breakout group leaders to prepare a single summary talk to be given the final day.**

Day 3, Thursday, April 26

International Perspective and IFE Science and Technology in the Long Term

7:30-8:00 Continental Breakfast

International Activities
8:00-8:30 FIREX Project (Hiroshi Azechi, ILE, Osaka, Japan)
8:30-9:00 HiPER and other EU Activities (Mike Dunne, UK)
9:00-9:30 IAEA Coordinated Research Program on IFE (Neil Alexander, GA)

9:30-10:00 Discussion on opportunities for international collaborations

10:00-10:15 Break

10:15 AM-12:00 PM – Contributed/Solicited talks (~ 5 @ 15-20 min each)
Other (non-driver) Enabling and Cross-Cutting Science and Technology

- A Survey of Advanced Target Options for IFE (John Perkins, LLNL)
- Ion-Driven Fast Ignition: Scientific Challenges and Tradeoffs (Juan Fernandez, LANL)
- Thick Liquid Protection for Inertial Fusion Energy Chambers (Per Peterson, UCB)
- Dry Wall Chamber Designs (Rene Raffray, UCSD)
- Status of Developing Target Supply Methodologies for Inertial Fusion (Dan Goodin, GA)

12:00-1:00 PM - Lunch

1:00-3:00 Poster Session (contributed posters)

3:00-5:00 PM - Breakout Session - IFE Planning*
Four groups. Same questions for each group:

- What are the elements of a compelling breakout strategy for IFE?
- What advances have to be made to make such a strategy credible?
- What advances can only be made with increased funding?
- Have views of an IFE development path changed since FESAC report? If so, how?

***Breakout group leaders to prepare a single summary talk to be given the final day.**

Day 4, Friday, April 27

Next Generation and Next Steps

8:00-8:30 Continental Breakfast

8:30-10:00 AM - Panel Discussion
Training the Next Generation: University Participation in HEDP and IFE Science and Technology
(5 minute introductions + Discussion)
(Bruno Bauer, UNR; Farhat Beg, UCSD; Linn Van Woerkom, OSU; Shahram Sharafat, UCLA; Brian Wirth, UCB)

10:00-10:15 Break

Summaries from Breakout sessions
(up to 30 minute presentation plus 15 minute discussion)

10:15-11:00 Wednesday Breakout Summary: HEDP Opportunities for IFE (Ed Synakowski, LLNL)
11:00-11:45 Thursday Breakout Summary: IFE Planning (Steve Dean, FPA)

11:45 AM - 12:00 PM - Concluding Remarks, Action Items, Next Steps

12:00 PM - Adjourn

Welcome and perspectives

Presentation to the Inaugural IFE Science and Technology Strategic Planning Workshop
San Ramon, California

Ed Synakowski
Fusion Energy Program Leader, LLNL

April 24, 2007

Work performed under the auspices of the U.S. Department of Energy
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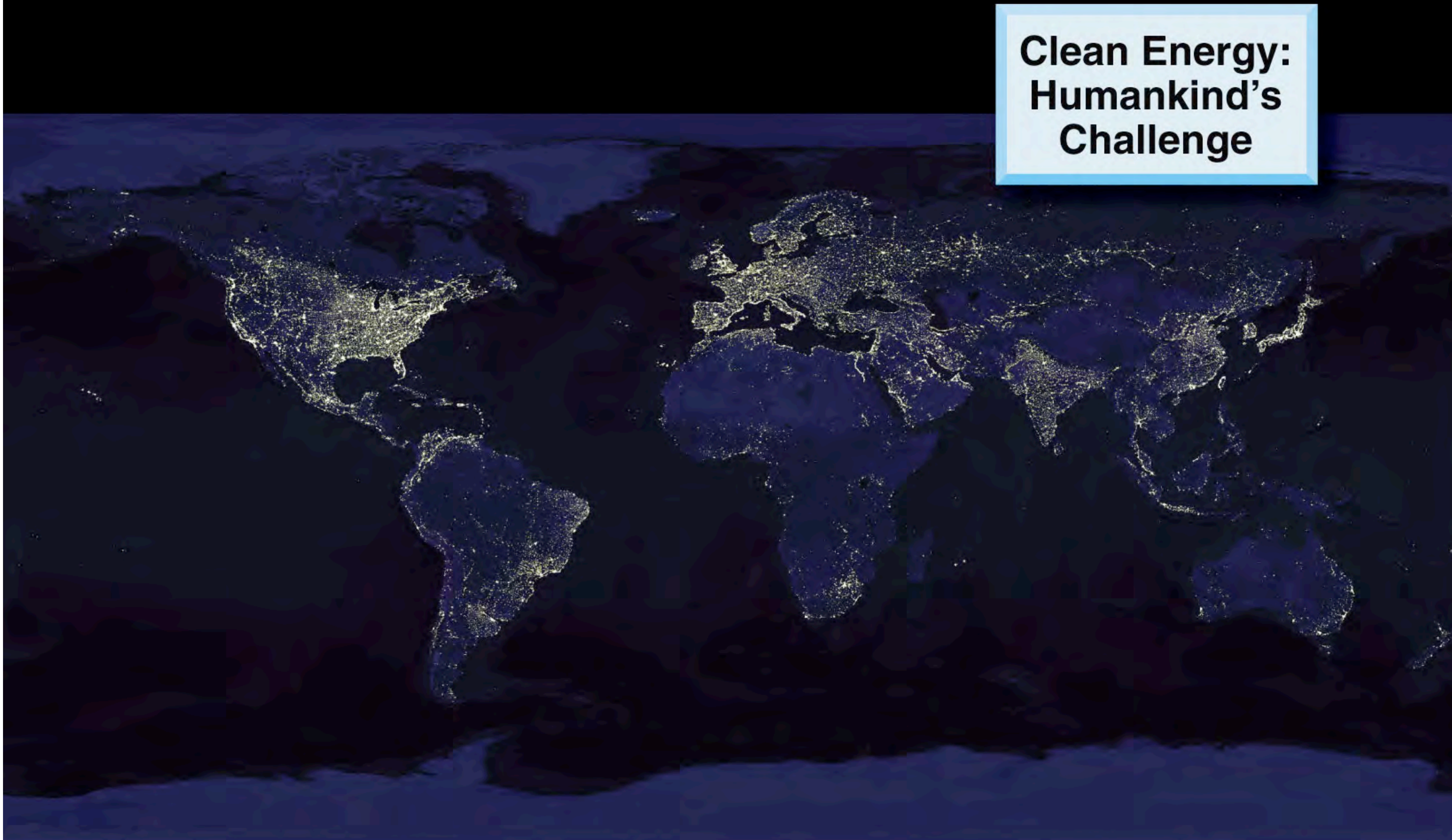
under Contract No. W-7405-ENG-48.

UCRL-PRES-230208

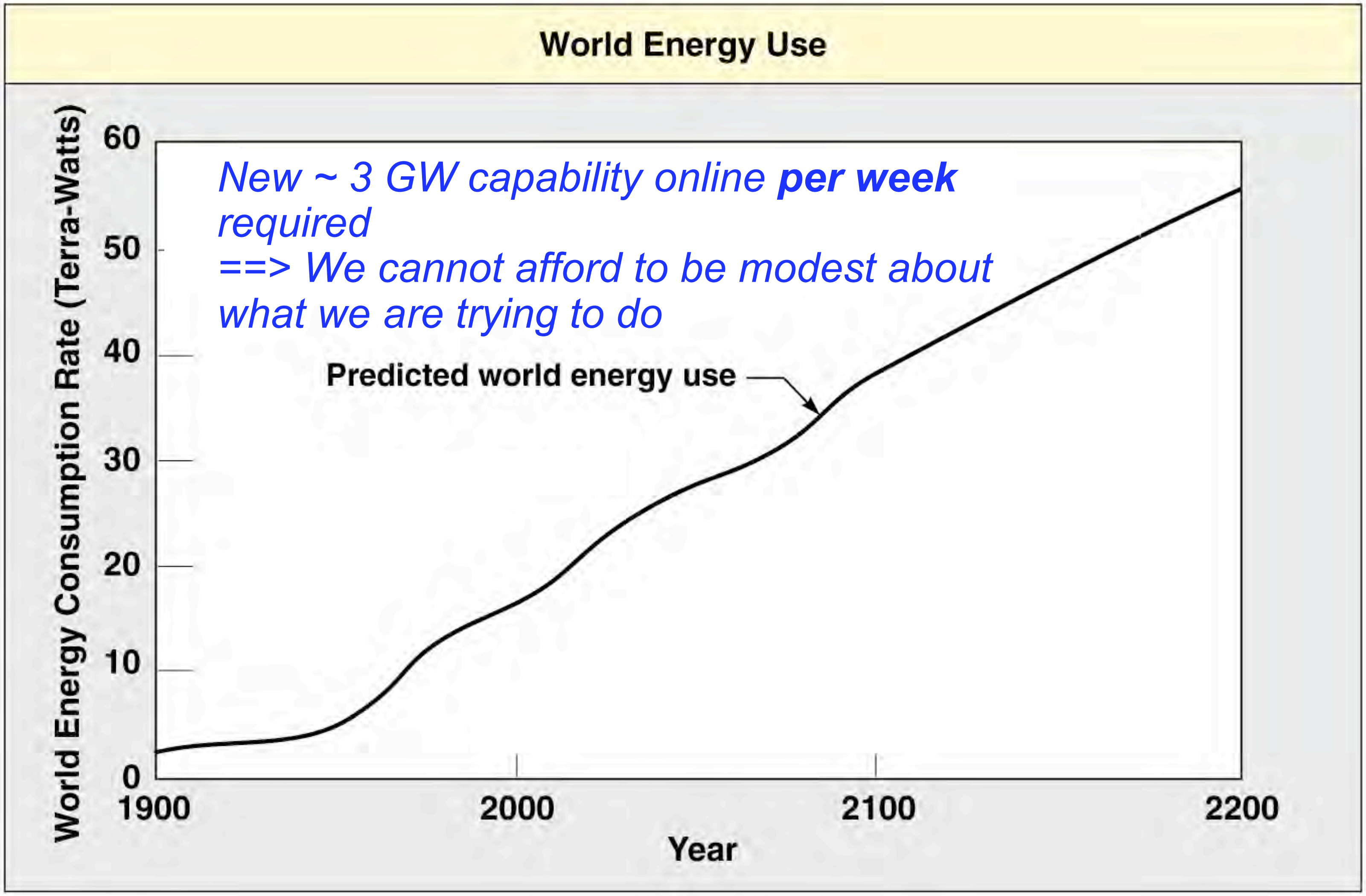
Changes - in world attitude, government policy, and science & technology - make this the time to assess the status of IFE and its science

- Global warming - dialogue has shifted from “whether” and “what if” to “what now”
- Our sponsors recognize the excitement and potential of HEDP, the science of the fusing IFE target
- A new age in the science of inertial fusion is upon us, including new tools and advanced computation
  - — their emergence for the study of high energy density systems and laboratory burning plasmas is generating a sense of urgency


Clean Energy:
Humankind's
Challenge

The projected energy demands are so remarkable they are difficult to grasp

The National Ignition Facility



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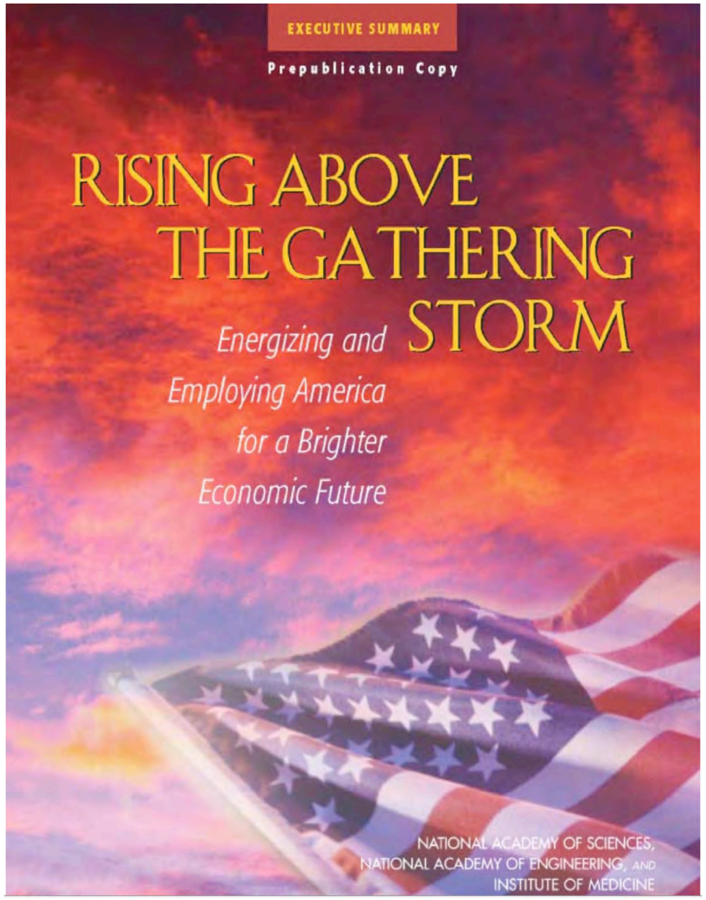
The quality and potential of the science of IFE has gained recognition at a high level

- High Energy Density Laboratory Plasma Physics (HEDLP, or HEDLP^2)- a new joint SC/NNSA Program is being formed. The IFE community can contribute to making this program strong and effective, and the IFE community can benefit in return
- There is a high level interest in developing HEDLP and making best use of this nation's facilities to advance it

The United States is re-thinking its approach to the physical sciences

- The Augustine Report, “Rising Above the Gathering Storm,” was taken seriously by the present administration
- A proposal has been made by this Administration to **double funding in the physical sciences over the next decade - the ACI -** but we have to compete for it
- Fusion energy research is in a position to gather some of this support in the long term

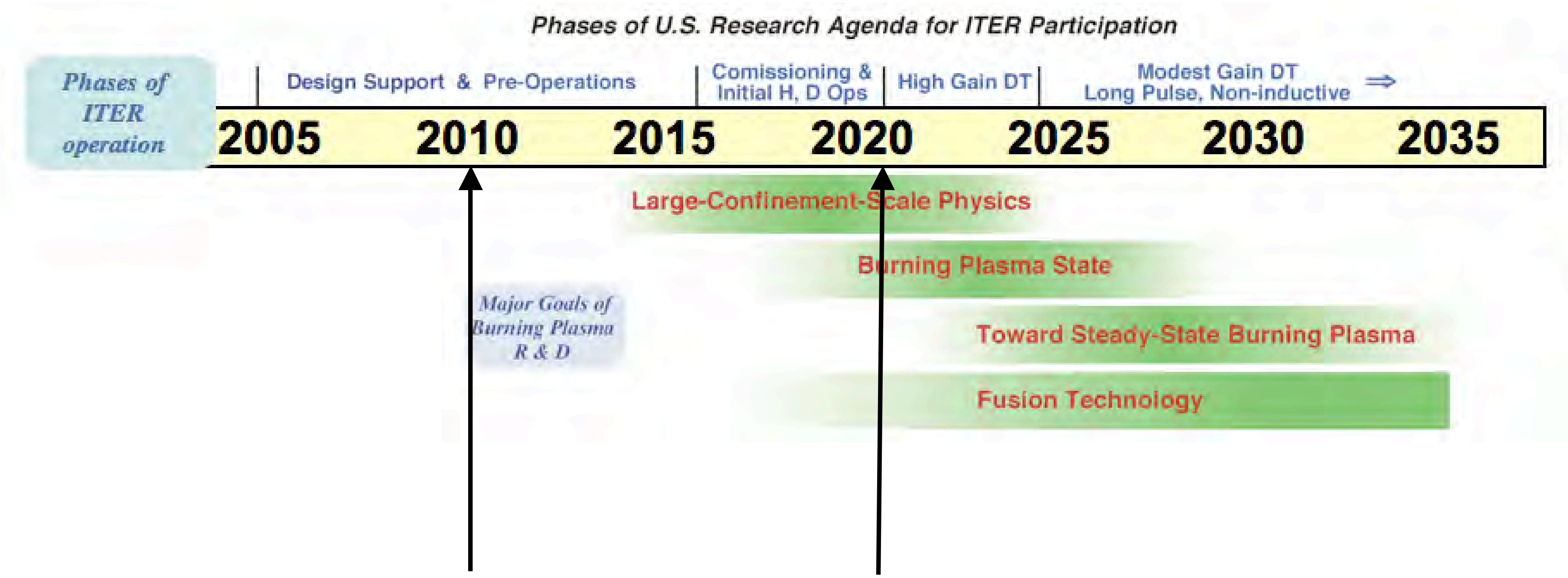


The stakes are so high that the world will benefit if IFE can be brought forward as a true alternate

- ITER will represent a tremendous advance for fusion energy. The science is rich and exciting. This nation’s involvement is predicated on ITER’s potential for advancing burning plasma science
- But magnetic fusion energy is not without risk. It is a tremendous integration challenge
- IFE presents a fundamentally different portfolio of possibilities and risks. It is smart business to develop alternative approaches in high stakes, challenging tasks

This Workshop can represent a step in clarifying the possible paths forward and the associated technical risks

Striking for ignition on NIF will long precede ITER burning plasma operations



First full scale ignition experiments

High gain ITER DT operations start

The question from the world upon ignition:
"What is your energy strategy?"

From U.S. MFE community EPAct report, May 2006

The science underpinning IFE, and how IFE advances it, needs to be clearly articulated

- There is no inconsistency in the goals of advancing fusion energy and performing great science.
- Right now, there is an opportunity to advance the support of IFE-related science in the form of HEDP
- The magnetic fusion energy community has worked long and hard at expressing its scientific goals and establishing metrics. The benefit has been real politically, and also with respect to advancing the science
- The inertial fusion energy community will benefit if it can sharpen its articulation of its science and technology goals

This Workshop can be a step in clarifying the scientific and technical depth associated with advancing IFE

The community needs to be prepared for the political and scientific impact of ignition

- No matter what one's perspective on IFE - huge fan, strong skeptic, or proponent of a particular approach - we cannot afford to be flat-footed upon success on NIF

This Workshop can be a step in sharpening a community vision of the implications and impact of ignition

The community will benefit from a strong common technical understanding of all of the major proposed approaches to IFE and recent progress

- What are the major breakout options, what is the science base, what is their maturity?

- What might a breakout strategy look like if it could be implemented with significant funding increases?

This Workshop can be a step in clarifying our readiness to carry out a robust IFE research program based on a strong HED science base

A successful workshop can be a step in a continuing community process to engage and energize our sponsors and sharpen our scientific vision

- Build on/work with
  - — a successful HAPL program that has promoted and represented IFE research for some years now
  - — investments made and progress with Z
  - — HIFS-VNL progress in compression & focus and aiming towards WDM science and IFE applications

- Promote ties and learning of how to work with the new joint HED LP Program and promote the use of NNSA and university programs in the general advance of HED LP

The first day concentrates on major program updates as well as cross-cutting and emerging science

- KrF, DPPSL, HIF, Z. Fast ignition. An emergent concept: MTF

- Emphasis on updates and then discussion

- End-of-day panel discussion:

  What can/should we do to be prepared to take advantage of growing interest in and funding for IFE that could be triggered by a variety of events (e.g., successful ignition on NIF, increase concern about global climate change, increase interest in domestic energy sources, etc.)?

Day 2: HEDP science and the intersection with IFE

- What is the present state of HED LP research and the new joint SC-NNSA Office?
  - — Ray Fonck (OFES-SC), Chris Keane (NNSA), Francis Thio (OFES) will present and discuss with you

- What are the HED LP opportunities on NNSA facilities?
  - — NIF, Omega, Z, Nike

- Breakout session: four groups, same questions for each group:
  - Focus on HED LP opportunities on NNSA and OFES facilities
  - Focus on ways of doing business - what works, where the obstacles?
  - Four leaders will work together to yield a joint report for Friday morning

- *I need your help on this*: I've been asked to report out from this meeting to the joint NNSA/Office of Science workshop on High Energy Density Laboratory Plasmas (HEDLP), called by Orbach and to be held in late May.

Day 3: International perspectives, contributed talks, and breakout strategies

- International updates and perspectives from the U.K. (Dunn) and Azechi (Japan)
- Contributions on cross-cutting and enabling technologies
  - — Advanced targets. Liquid walls, dry wall chambers, target fabrication
- *Breakout session at the end of the day. Four groups: breakout strategies*
  - *What are the elements of a compelling breakout strategy for IFE?*
  - *What advances have to be made to make such a strategy credible?*
  - *What advances can only be made with increased funding?*
  - *Have views of an IFE development path changed since FESAC report? If so, how?*
- Four breakout leaders will work to develop a report for Friday morning

The Steering Committee for this meeting

- Ed Synakowski, Chair, Lawrence Livermore National Laboratory
- Ron Davidson, Princeton Plasma Physics Laboratory
- Stephen O. Dean, Fusion Power Associates
- Dan Goodin, General Atomics
- John Lindl, Lawrence Livermore National Laboratory
- Grant Logan, Lawrence Berkeley National Laboratory
- Keith Matzen, Sandia National Laboratories
- Wayne Meier, Lawrence Livermore National Laboratory
- David D. Meyerhofer, University of Rochester
- Steve Obenschain, U.S. Naval Research Laboratory
- John Sheffield, University of Tennessee

We have an opportunity to publish a conference proceedings

- Journal of Fusion Energy - Steve Dean, ed.

- Regard it, in part, as an update to the Linford FESAC report - what has changed in IFE-related science and technology development. Capture the major conclusions or thrusts of breakout discussions

- For presenters - your contributions of a few pages, with some figures, are sought by the end of May

Thanks are due…

- Thanks especially to Mila Shapovalov for her tremendous effort in pulling this together and enabling what should be a productive community experience.

UCRL-PRES-230116

Setting the Stage for IFE & Workshop Overview

Wayne Meier
LLNL

IFE Science and Technology
Strategic Planning Workshop
April 24-27, 2007
San Ramon, CA

Work performed under the auspices of the U. S. Department of Energy by University of California Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

Outline

- Setting the Stage
  - Brief synopsis of recent history of IFE research
  - Review of findings of FESAC IFE panel report
  - Previous recent development plans
- Workshop Overview

Progress on various approaches to IFE has continued despite difficult circumstances

- Laser-driven IFE
- Heavy Ion Fusion (HIF)
- Z-IFE
- Fast Ignition

Laser IFE

- Laser-driven IFE R&D is being conducted as part of the High Average Power Laser (HAPL) program.
- HAPL has been support by yearly Congressional language and funded through NNSA.
- HAPL includes both kryton-fluoride (KrF) laser and Diode Pumped Solid State Laser (DPSSL) options
- Also includes target physics, target fab and injection, materials and chamber R&D in an integrated study.
- Presentations will be given by John Sethian (overall HAPL plus KrF) and Al Erlandson (DPSSL).
- Thursday’s talk by Rene Raffray on dry-wall chambers and several posters provide additional detail.

Heavy Ion Fusion (HIF)

- Funded by OFES
- Last major IFE focused activity concluded with an integrated conceptual design, the Robust Point Design, published in 2003.
- Since 2003 the focus of the Heavy Ion Fusion Science Virtual National Lab (HIFS-VNL) has on beam compression and focusing in plasmas for warm dense matter targets in the near term and IFE in the long term.
- The goal of fusion energy remains a strong interest and motivation for those in the VNL, and innovative ideas continue to emerge.
- Grant Logan, Director of the VNL, will discuss in detail.
- Per Peterson's talk (Thursday) on thick liquid chambers supports HIF and other IFE approaches.

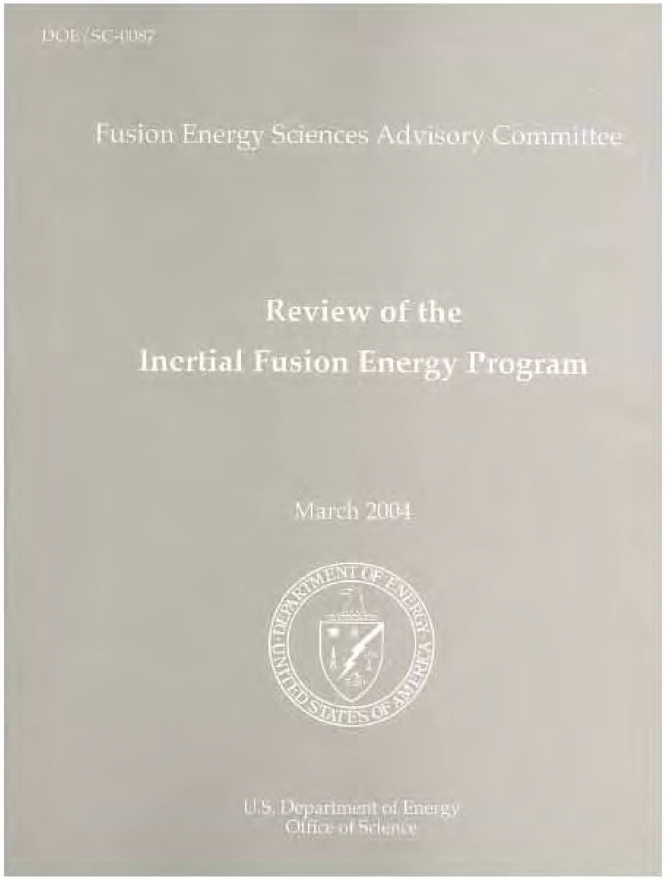
Z-IFE

- Z-pinch driven IFE (Z-IFE) was studied at a low level at SNL for many years.
- Congressionally mandated funding through NNSA in FY04-05 and internal funding in FY06 allowed SNL to engage the broader IFE community to advance the concept in an integrated way.
- Chamber is based on thick-liquid wall concept and the R&D is synergistic with the HIF approach.
- Craig Olson will give an overview of the status of Z-IFE research.

Fast Ignition

- Fast ignition theory and experiments are support by OFES.
- Benefits of higher target gain at low drive energy are of interest to all IFE approaches.
- Also strong pure science interest in the extreme physics encountered in FI.
- This is broad international interest in FI and it is the focus of Japan's IFE program.
- Mike Campbell will provide an overview of FI as a cross-cutting approach to IFE.
- On Wednesday, Riccardo Betti will discuss scientific aspects in more detail.
- On Thursday we will hear about international activities.

The 2004 FESAC IFE Panel report serves as a starting point for our workshop discussions



Appendix B
FESAC Panel on the Inertial Fusion Energy Program

Professor James Asay, *Washington State University*
Professor Riccardo Betti (Vice Chair), *University of Rochester*
Mr. Michael Campbell, *General Atomics*
Dr. Phillip Colella, *Lawrence Berkeley National Laboratory*
Dr. Jill Dahlburg (Vice Chair), *Naval Research Laboratory*
Professor Jeffrey Freidberg, *Massachusetts Institute of Technology*
Professor Jeremy Goodman, *Princeton University*
Professor David Hammer, *Cornell University*
Dr. Joseph Hoagland, *Tennessee Valley Authority*
Dr. Steve Jardin, *Princeton Plasma Physics Laboratory*
Dr. John Lindl, *Lawrence Livermore National Laboratory*
Dr. Rulon Linford (Chair), *University of California (Retired)*
Dr. Grant Logan, *Lawrence Berkeley National Laboratory*
Dr. Keith Matzen, *Sandia National Laboratory*
Professor Gerald Navratil, *Columbia University*
Dr. Arthur Nobile, *Los Alamos National Laboratory*
Dr. John Sethian, *Naval Research Laboratory*
Dr. John Sheffield, *University of Tennessee, Knoxville*
Dr. Mark Tillack, *University of California, San Diego*
Dr. Jon Weisheit, *Los Alamos National Laboratory*

Progress has been impressive and quality of science and technology research excellent

• "Overall, they [panel members not participating in IFE] were **very impressed by the progress** across the program…

•…The recent progress related to these approaches is substantial and the **quality of the science and engineering research is excellent**.

• …All approaches are currently on track for developing the science and technology to properly evaluate their potential for IFE.

•…the planned termination of technology programs in support of the HI approach is not consistent with their importance to HI-IFE."

Updates on progress will be given today.

Benefits of FI were recognized but deemed premature as the baseline approach

•"…**each of the approaches to IFE may benefit** if the technique of Fast Ignition proves effective.

•…it would be **premature** for any of the IFE approaches to rely on the success of FI to achieve an attractive fusion energy system.

• During the next several years, there is an opportunity to assess the potential of the FI concept utilizing facilities in both Japan and the US (OMEGA, Z, and possibly NIF) through modest OFES investments."

FI is discussed on Tuesday and Wednesday.
International interest on Thursday AM.

Synergy with the ICF program was noted

- "The Panel acknowledges this vital role of the ICF program ...
- …notes the **tremendous leverage** that allows the comparatively modest funding for IFE-specific programs to continue to yield important advances.
- This is a **synergistic relationship** where IFE research also directly benefits the NNSA mission."

Synergies and coordination with NNSA ICF programs is covered on Wednesday.

IFE contributes to HEDP and other areas of Science

- "The Panel also found that IFE capabilities have the potential for **significantly contributing to HEDP and other areas of science**.
- …Investigations of the Fast Ignition concept can lead to exploration of exotic HEDP regimes."

Energy-related HEDP is covered on Wednesday.

The need for a coordinated program(s) was recognized by the panel

"…the Panel agrees with the IFE community that the **most efficient way** to achieve the ultimate goal of fusion energy **is to carry out a coordinated program** with some level of research on all of the key components (targets, drivers, and chambers), always keeping the end product and its explicit requirements in mind."

Progress and plans for IFE development are covered on Tuesday and Thursday.

Differences in OFES and NNSA strategies were noted

“Finding: The Panel recognizes and respects the reasons for the **differences in near-term focus of OFES and NNSA sponsored programs**. Although near-term strategies differ, the ultimate goal of all IFE research is fusion energy production. The long-term potential for fusion power provides an exciting and unifying purpose for all IFE research activities.”

We will hear from OFES and NNSA leaders on the newly formed High Energy Density Laboratory Plasma (HEDLP) joint program on Tuesday AM.

The scientific challenges are are attracting outstanding researchers to IFE

"Finding: IFE research involves a rich set of scientific challenges. Substantial advances in a spectrum of scientific disciplines will be required to effectively assess the long-term potential of IFE. **Many outstanding researchers from academia as well as federal laboratories are pursuing a range of exciting IFE science topics**."

The need to continue to develop and engage the next generation of researchers will be addressed Friday AM.

Interplay between science and technology and need for prioritized R&D were noted

"Finding: Understanding the interrelated scientific and technological issues of the key components of IFE within the framework of an integrated system is an essential input for prioritizing IFE research activities, whether for the science focused OFES program or for the NNSA program. **Careful prioritization is particularly important** given the limited resources available to these IFE activities."

The spectrum of inertial fusion science and technology is addressed throughout this workshop. Prioritization is not an objective of this workshop.

Need for coordination was cited

“Finding: Carrying out a coordinated IFE research program allows a more efficient approach for developing a fundamental understanding of the science that is necessary for IFE.”

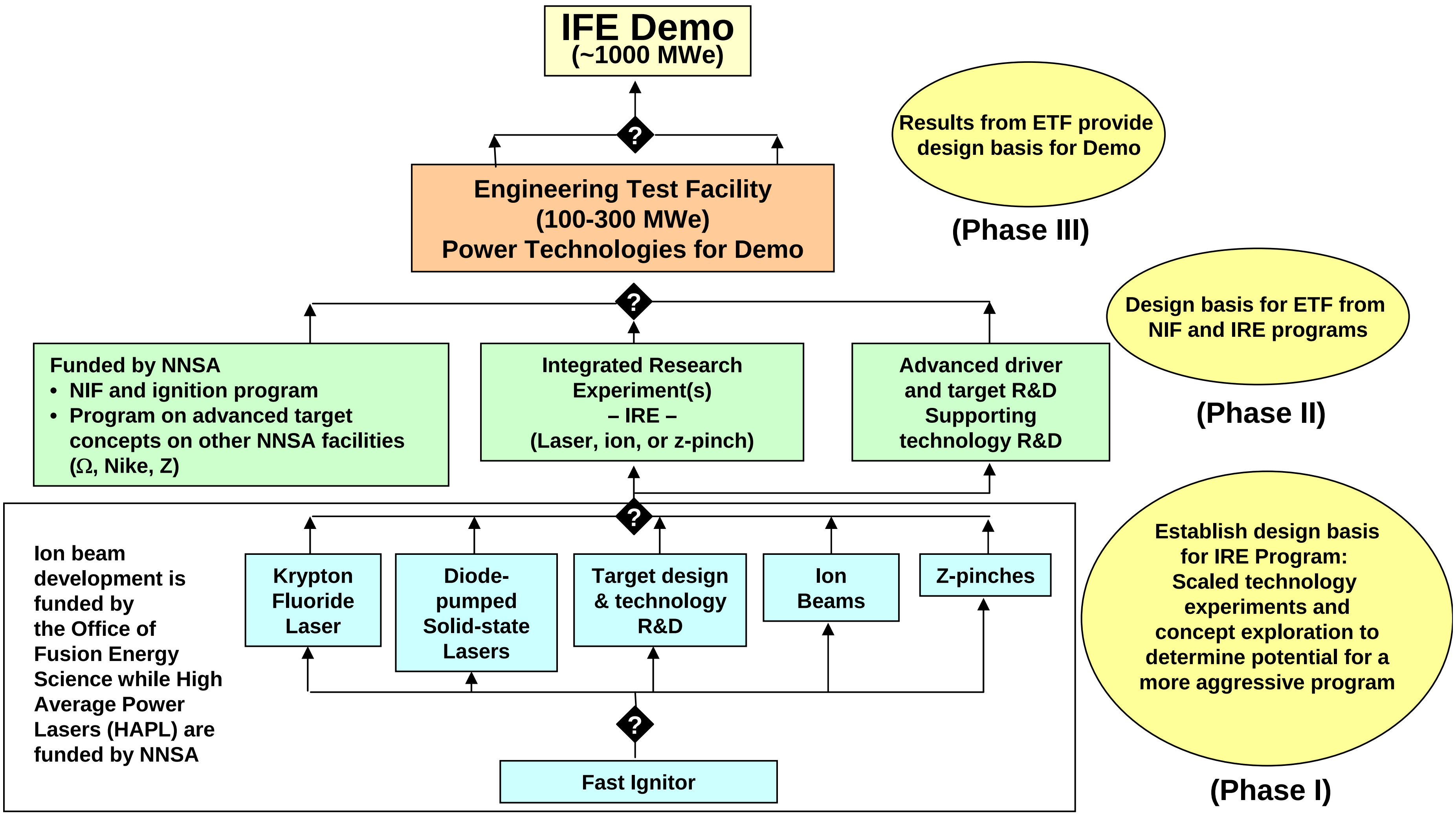
Coordination has been difficult given the diverse and often unreliable funding stream. This is a topic for the Wednesday PM break-out session.

Opportunities exist for better coordination between IFE and HEDP

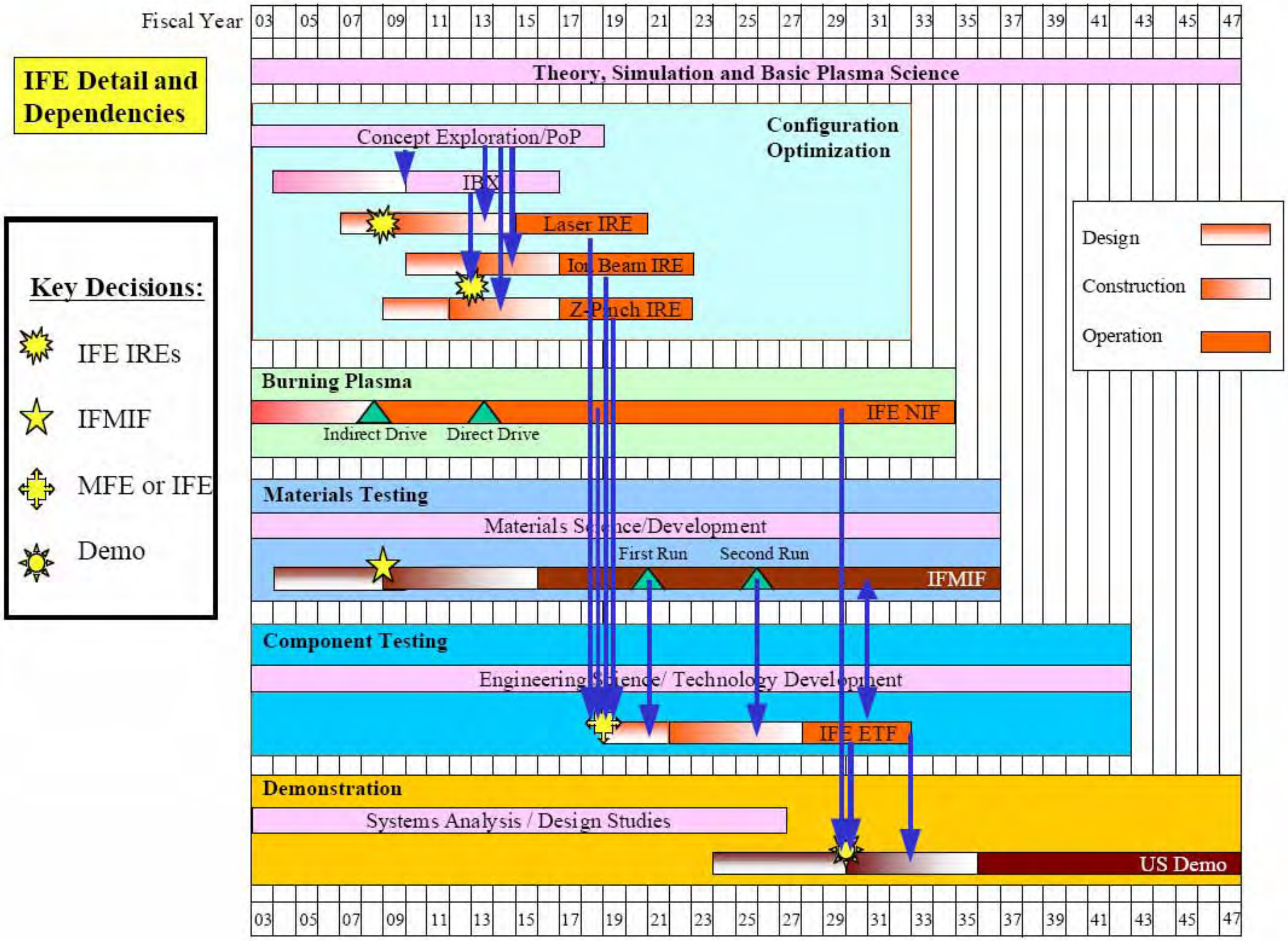
"**Finding:** The scientific and technical challenges posed by IFE, along with their many connections to HEDP, and the grand ultimate purpose of fusion power highlight both the need and the opportunity to attract outstanding researchers for future success. In order to identify and exploit key opportunities and synergies with HEDP and other exciting topics, **improved coordination is needed between various scientific communities**. The series of workshops on laboratory astrophysics with lasers is a model that could be emulated."

This is essentially the focus of Tuesday's agenda.

IFE Development plan circa Snowmass (2002)



IFE development plan from FESAC planning activity (2003)



Workshop overview

- First day (Tues, 4/24)
  - Updates on status, near term plans and long-range visions for different approaches to IFE
  - Fast ignition overview
  - Magnetic fields and inertially confined plasmas
  - Panel on preparing for a growing interest and funding for IFE
- Second day (Wed, 4/25)
  - Joint OFES/NNSA program on HEDLP
  - ICF/HEDP facilities and R&D
  - Breakout session on HEDP/IFE synergy and coordination

Workshop overview (cont)

- Third day (Thurs, 4/26)
  - Report on selected international activities and programs
  - Advanced targets, chambers, and target fabrication
  - Poster session
  - Breakout session on IFE development plans
- Forth day (Wed, 4/27 AM)
  - Panel on university participation in IFE/HEDP
  - Report back from Tues and Wed breakout sessions
  - Discussion of next steps

Thank you for coming.
Have a productive workshop!

PART I: The HAPL Program:
Developing science & technologies for Laser Fusion <u>Energy</u>

Presented by J.D. Sethian
Plasma Physics Division, Naval Research Laboratory

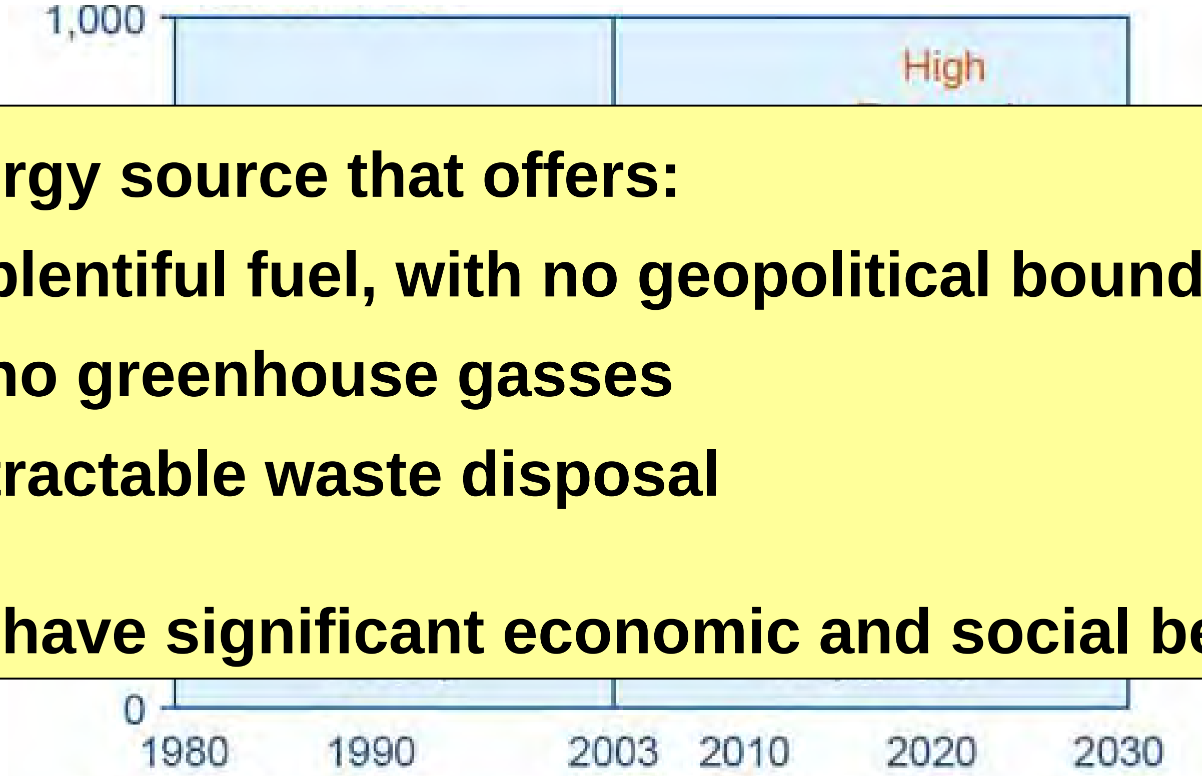
Government Labs
1. NRL
2. LLNL
3. SNL
4. LANL
5. ORNL
6. PPPL
7. SRNL
8. INEL

Universities
1. UCSD
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. UC Santa Barbara
7. UC Berkeley
8. UNC
9. Penn State Electro-optics

Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. FTF Corporation
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI

Fusion energy is a worthy goal

World Marketed Energy Consumption, 1980-2030
Quadrillion BTU



An energy source that offers:

- **plentiful fuel, with no geopolitical boundaries**
- **no greenhouse gasses**
- **tractable waste disposal**

Would have significant economic and social benefits!

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2003* (May-July 2005), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2006).

Prescription for a viable Fusion Energy R&D effort

Focused on energy mission

Make a convincing case it can be done

Staged program with clear cut goals and objectives, with defined off ramps

ROI (return on investment)

Premium on minimizing development costs

-and-

Relatively short development time

"Business Model" for the HAPL Program is based on lowering development costs and minimizing risk

1) V*alue Simplicity*

Leads to an attractive power plant

2) Leverage off other programs

ICF, MFE, HEDP, Materials science, ABM program, etc

3) Pick approaches that are modular

Allows subscale development

4) Encourage competition & innovation.

Competition is good

5) Develop science & technology as an integrated system

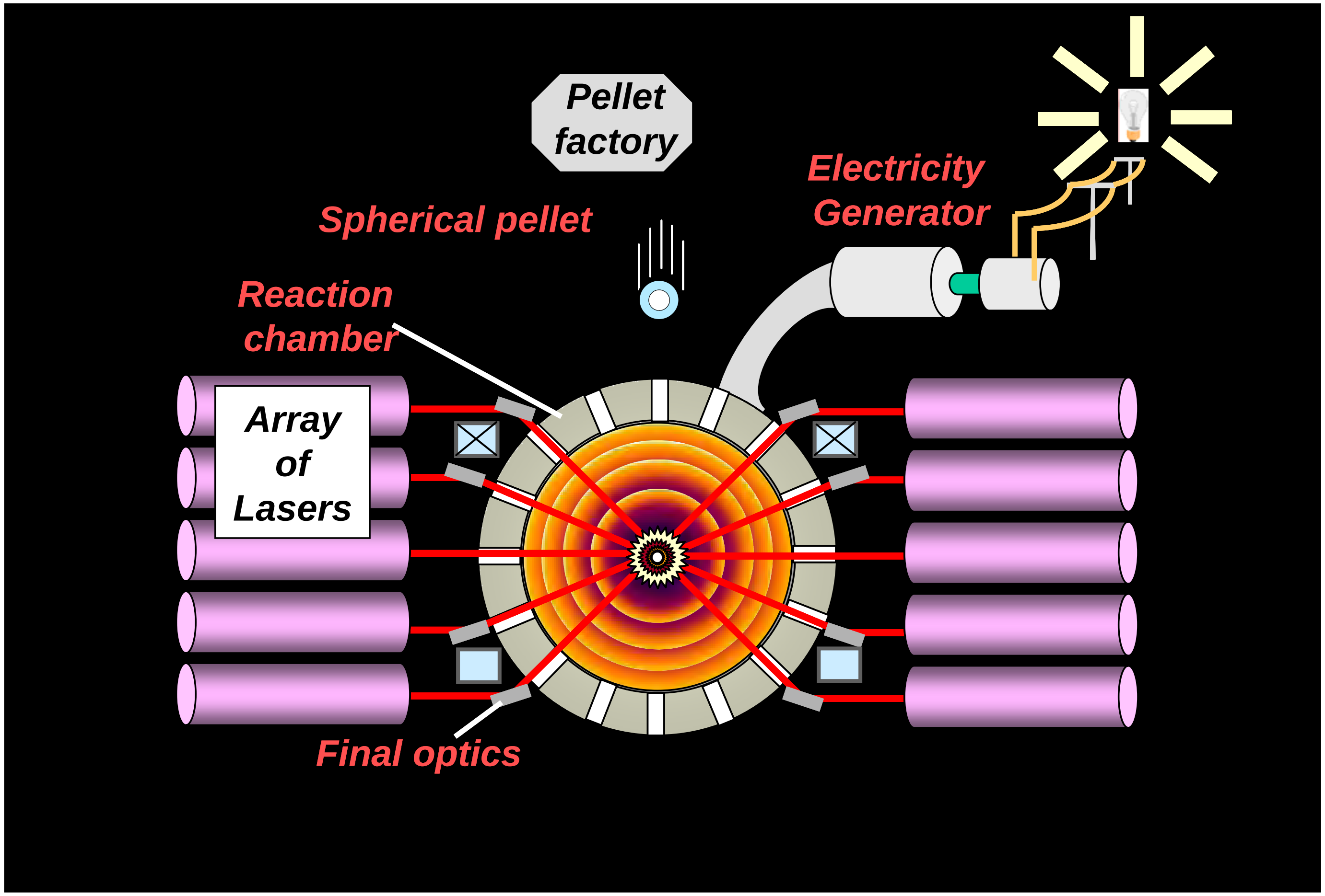
Lowest risk approach to an attractive system

6) Staged program

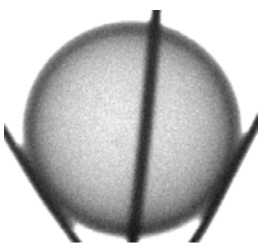
we are developing the science, technology and architecture for a laser fusion power plant...

Because we actually plan to build one

We have chosen to develop inertial fusion energy based on lasers, direct drive targets, and solid wall chambers



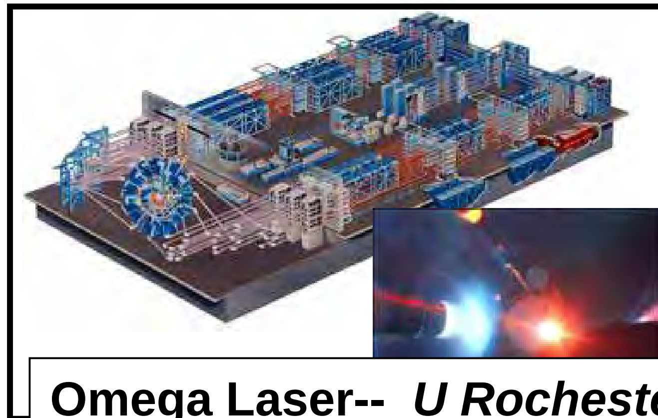
Why choose IFE, with lasers, direct drive targets, and dry wall chambers

Why IFE?	Separable components
Why Laser Fusion?	Large physics data base from ICF program Lasers/optics developed under ICF/industry venues Laser is MODULAR.. build one, you've built them all
Why Direct Drive?	Simplest physics (albeit still very challenging) Target physics amenable to changes (shock ignition) Simplest targets >> facilitates mass production No preferred direction of illumination No debris to recycle
	
Why Solid Wall?	Simplest design Comparatively easy to change based on R&D Most issues can be resolved sub scale

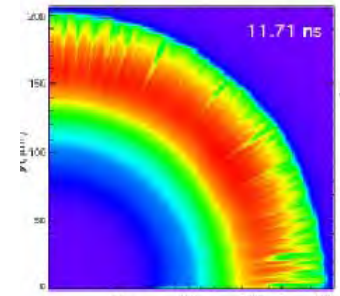
Disclaimer: Of course we are always open to other ideas (e.g. liquid walls, FI)
If someone develops them, we will be happy to steal them

Target physics based on large body of work in the US ICF Program

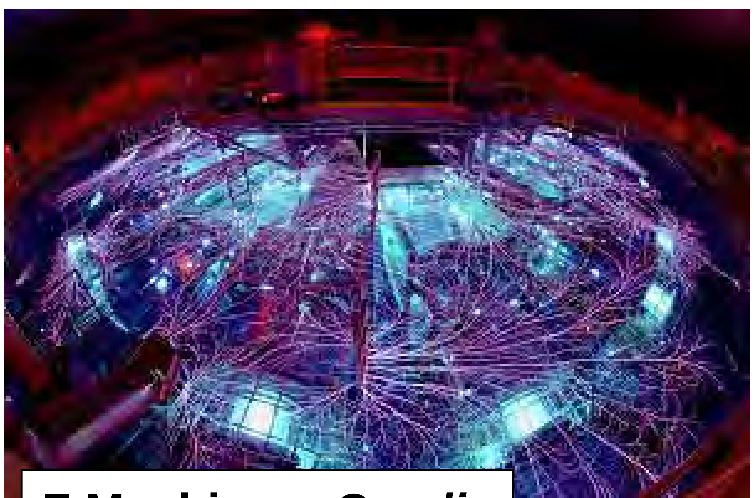
Nike Laser-- *NRL*



Omega Laser-- *U Rochester*



2-D modeling

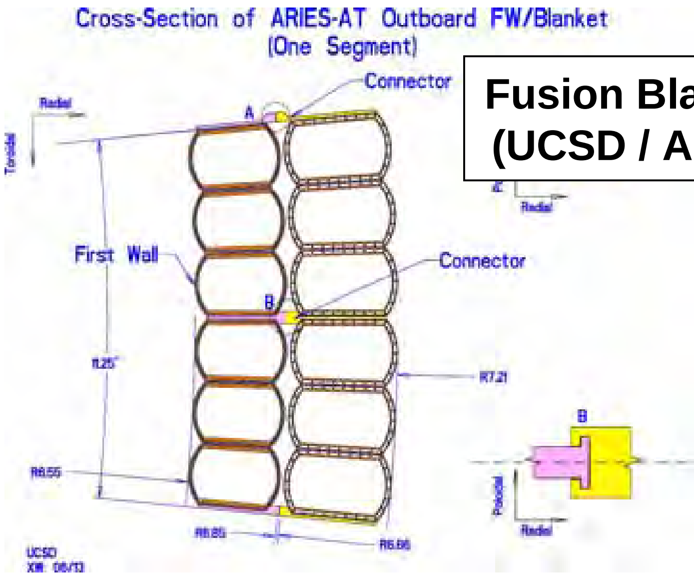


Z Machine-- *Sandia*

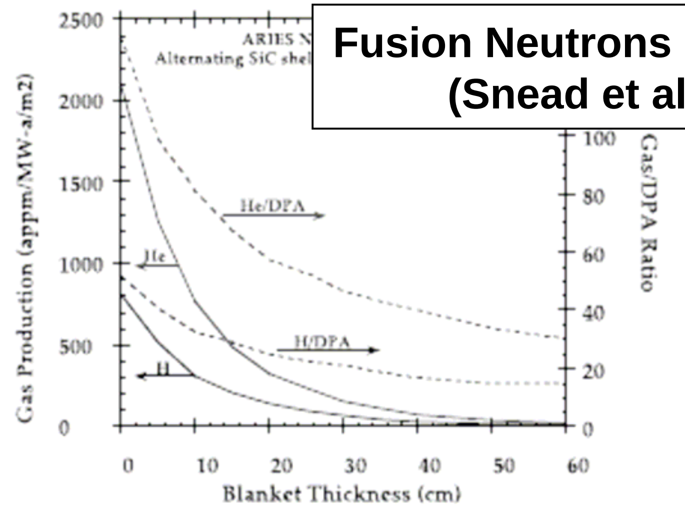
National Ignition Facility-- *LLNL*

Chamber/Blanket work builds on extensive R&D in the US & International MFE Program

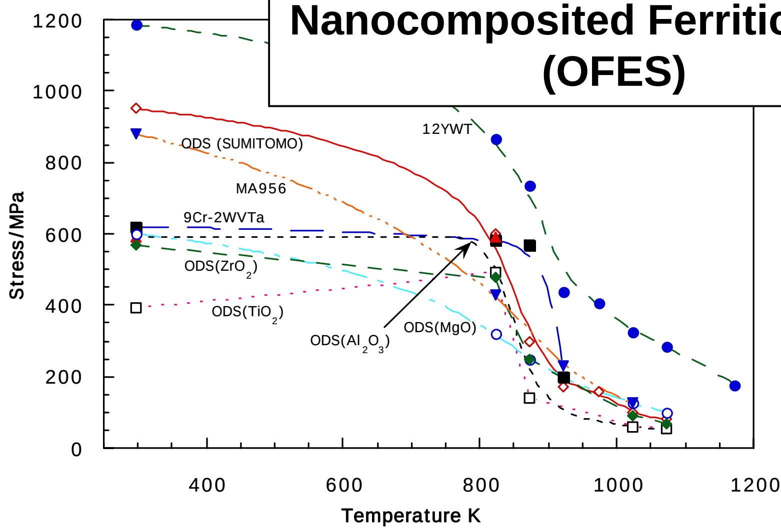
Fusion Blankets (UCSD / ARIES)



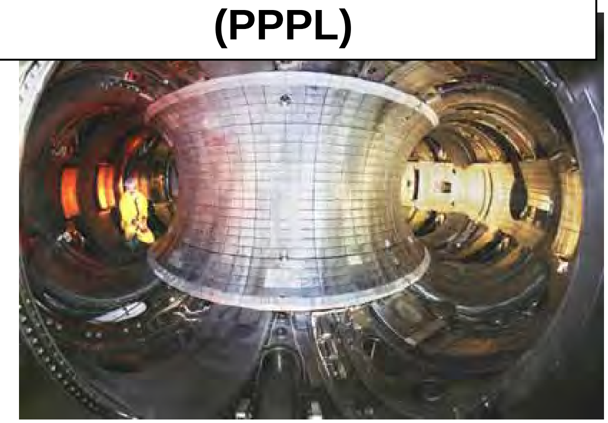
Fusion Neutrons in SiC (Snead et al)



Nanocomposited Ferritic & ODS (OFES)



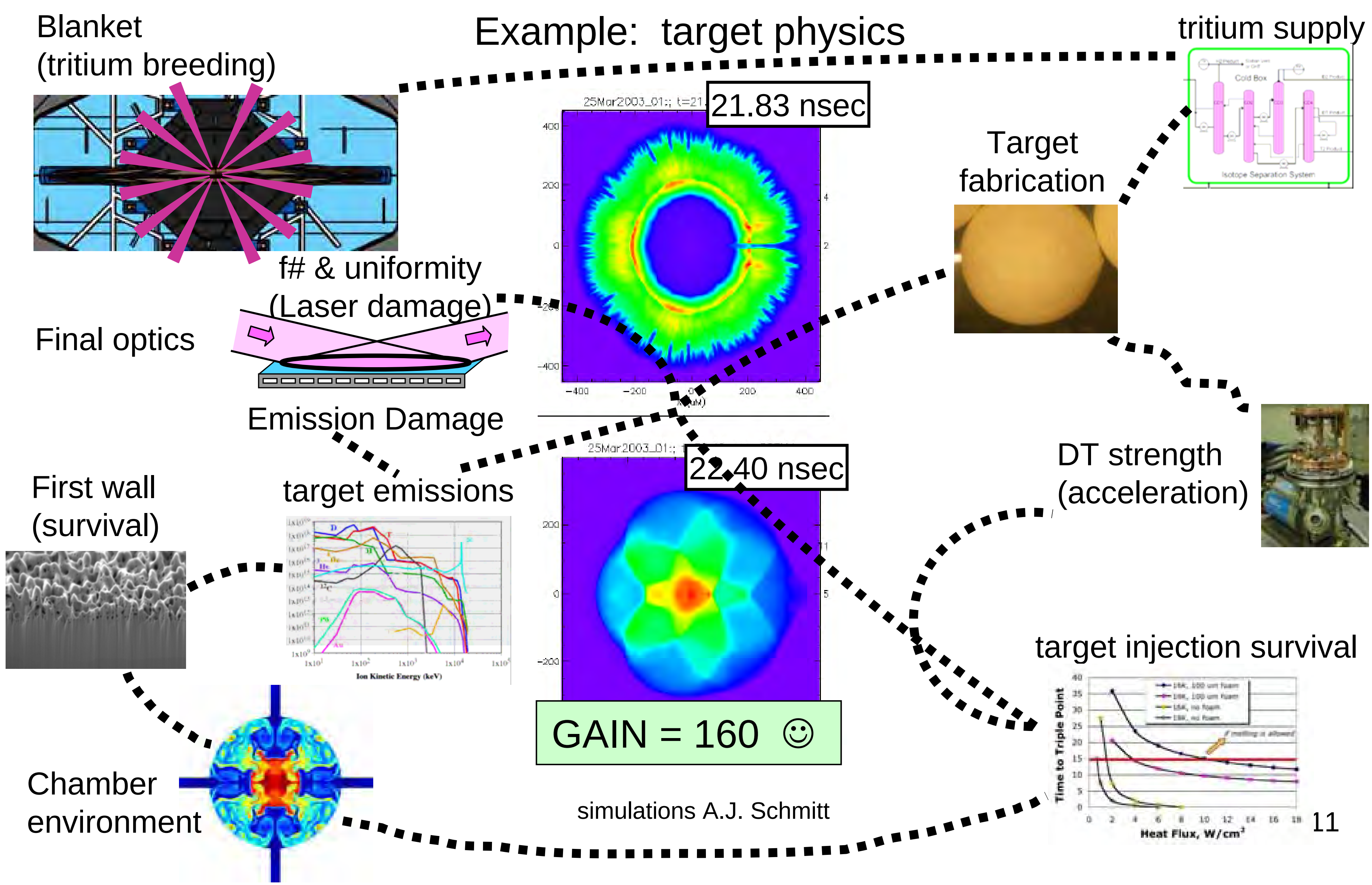
Fusion Systems Engineering (PPPL)



#20

The HAPL Program is developing two types of lasers We encourage competition. It leads to innovation and a better product. And leads to it faster

The integrated approach is <u>much</u> harder, but <u>much</u> more likely to "yield" something that works!

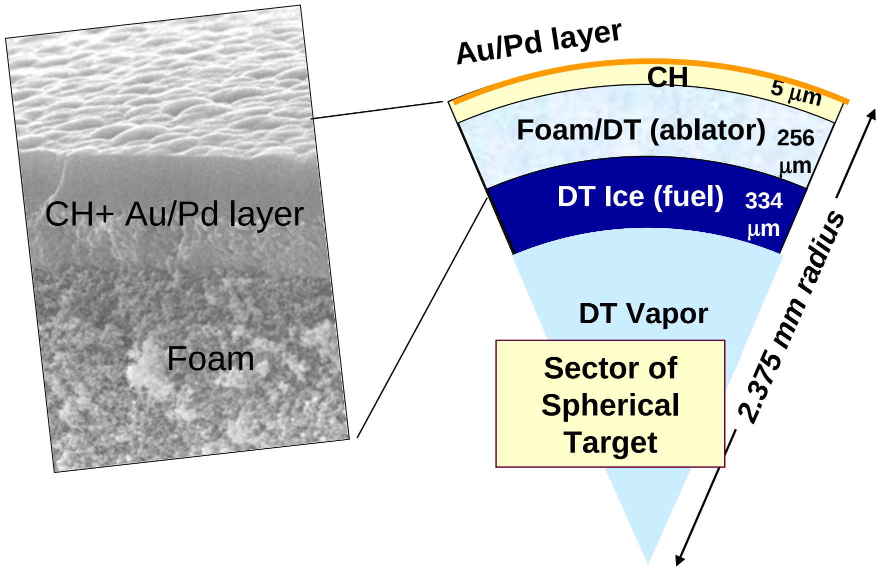


Summary of progress—
Target fabrication and target engagement
(see presentation by D. Goodin)

TARGET FABRICATION

Accomplishments
- Foam shells that meet specs
- Produced gas tight overcoats
- Demonstrated smooth Au-Pd layer
- Demo fluidized bed layering @ room temp

Need to do
- Increase shell yield
- Overcoat thickness
- Fluidized bed at cryo temperatures



TARGET INJECTION / ENGAGEMENT / TRACKING

Accomplishments
- Developed concept
- Demonstrated key principles on bench
- Meet most all specs

Need to do
- Meet all specs
- Integrated bench test

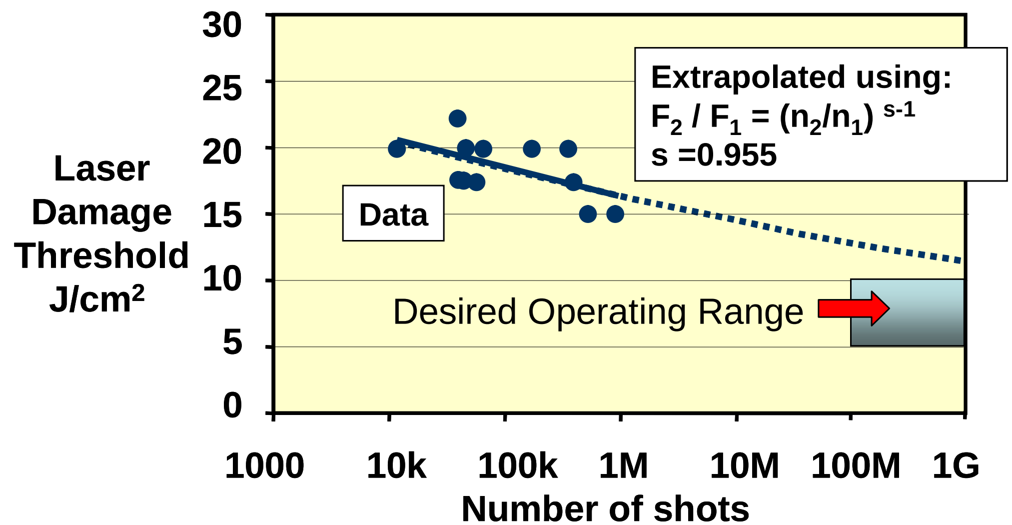
GA, UCSD, Schafer, LANL, AER

Mirror steering test

Summary of progress:
Final Optics

Accomplishments:

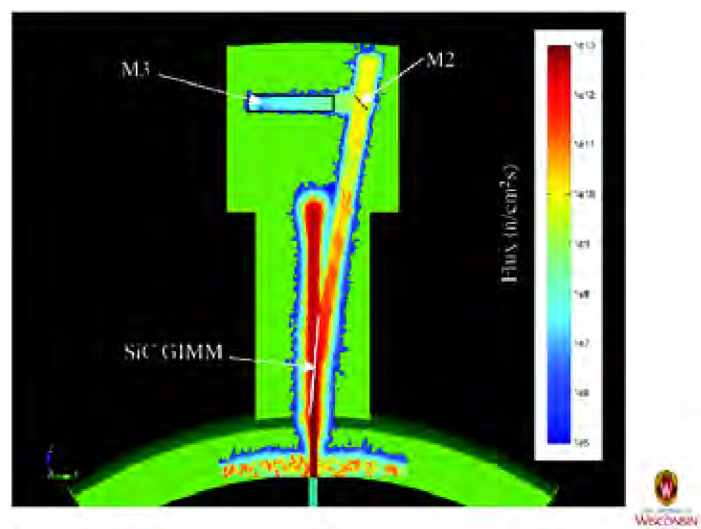
- Developed GIMM to meet Laser Damage threshold specs (based on ~ 1 M shots)
- Developed final optics train that meets neutronics requirements



Need to do:

- Verify to > 300 M shots
- Demo with larger areas
- Evaluate alternatives
  - Dielectric
  - Fresnel lens

3-D calculation of neutron flux



UCSD, PLEX LLC, Wisconsin, Penn State E-O, LLNL

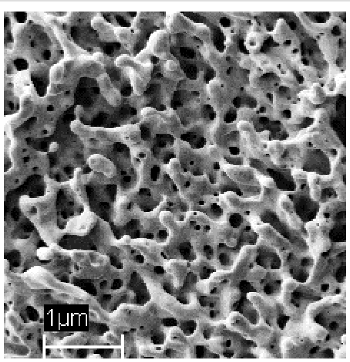
Summary of progress—
Chambers (First Wall/Substrate/Blanket)

Accomplishments:

- Bonding
- Thermo-mechanical cycling
- Pumping/chamber clearing
- Operating window
- Blanket/breeding/thermal cycle

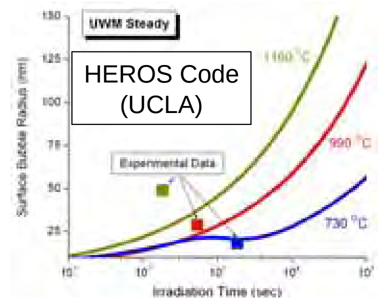
Need to do:

- helium retention
- carbon retention

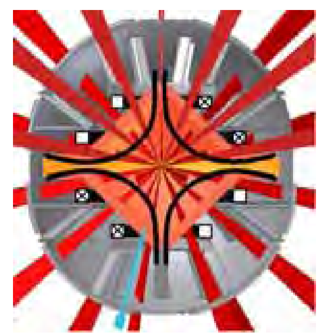


Our "three step plan"

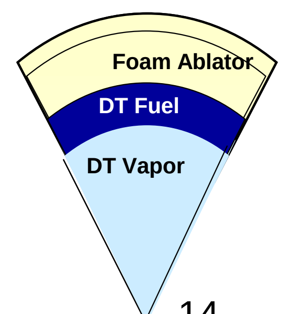
1. Materials Science Research



2. Magnetic Intervention

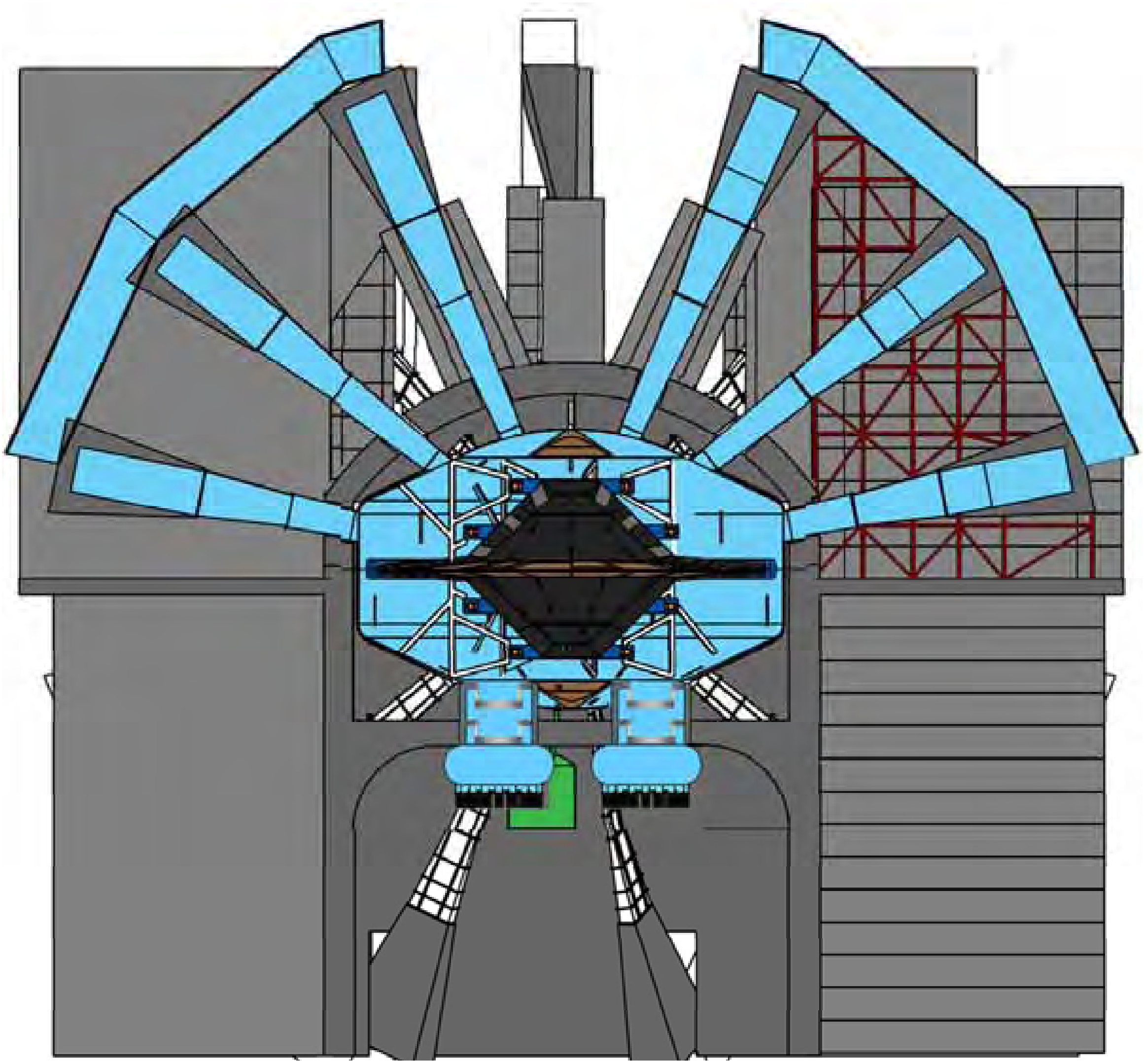


3. Revisit target design



UCLA, ORNL, NRL, Wisconsin, UNC, SNL, UCSD, LLNL, Ultramet, PPI, etc

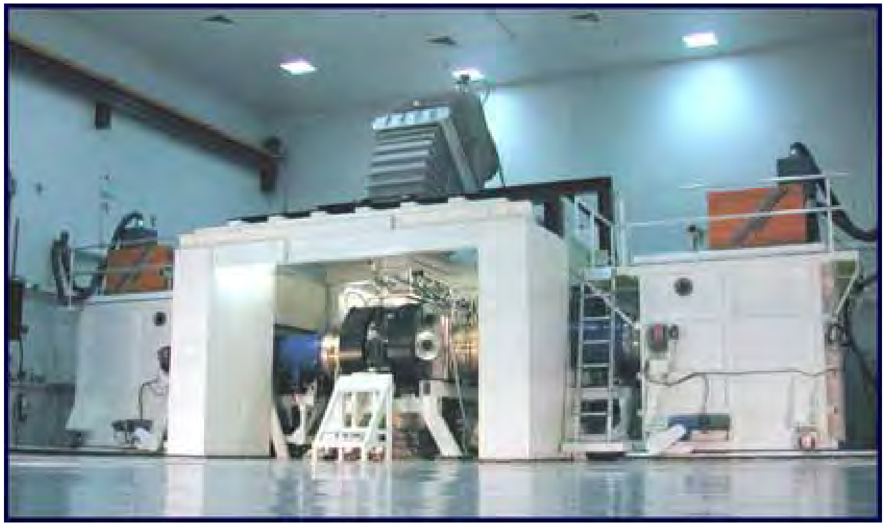
We are developing a chamber concept based on Magnetic Intervention



UCSD, Wisconsin, PPPL, AER, Voss, NRL

Part 2: KrF Laser development

NRL Laser Fusion



Electra:
Rep-Rate
Durability
Efficiency
Cost

NRL
- **M. Wolford**
- **J. Giuliani**
- **M. Myers**
- **S. Obenschain**

Commonwealth Tech
- **F. Hegeler**
- **M. Friedman**
- **T. Albert**
- **J. Parish**

RSI
- **P. Burns**
- **R. Lehmberg**

SAIC
- **R. Jaynes**
- **A. Mangassarian**

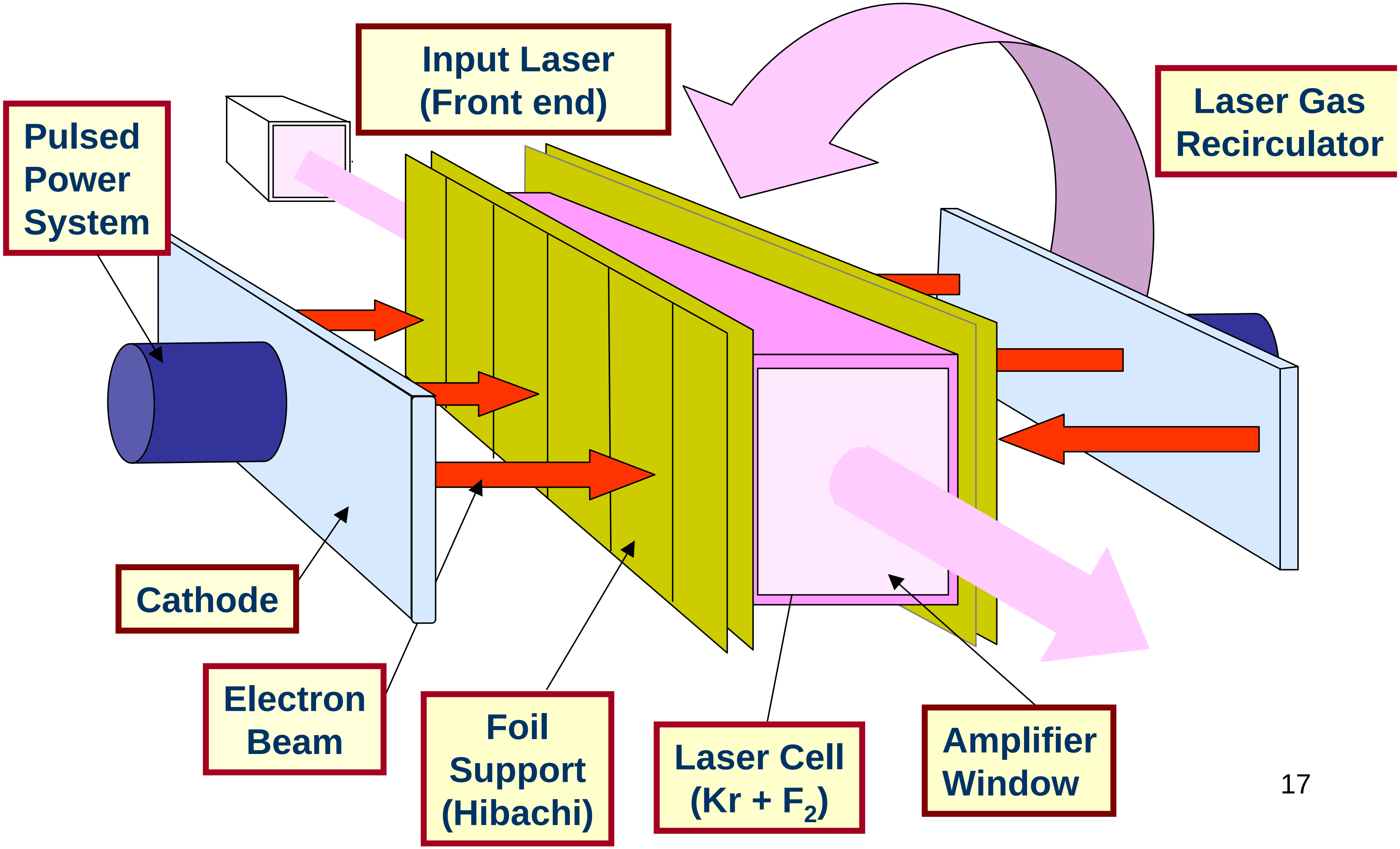
Georgia Tech
- **S. Abdel-Kahlik**
- **D. Sadowski**
- **K. Schoonover**

Nike:
Laser-target physics
E-beam physics
on full scale diode

The key components of a KrF Laser

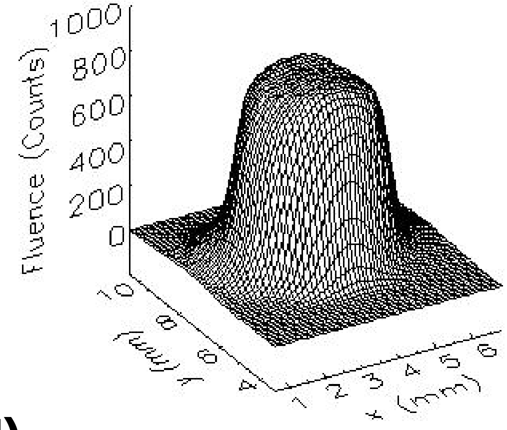
NRL Laser Fusion

Energy + (Kr+ F_2) $\Rightarrow$ (KrF)* + F $\Rightarrow$ Kr + F_2 + $h\nu$ (λ = 248 nm)



Why we like KrF Lasers for Inertial Fusion Energy

Demonstrated very uniform laser beam (Single shot):
minimizes hydrodynamic instabilities



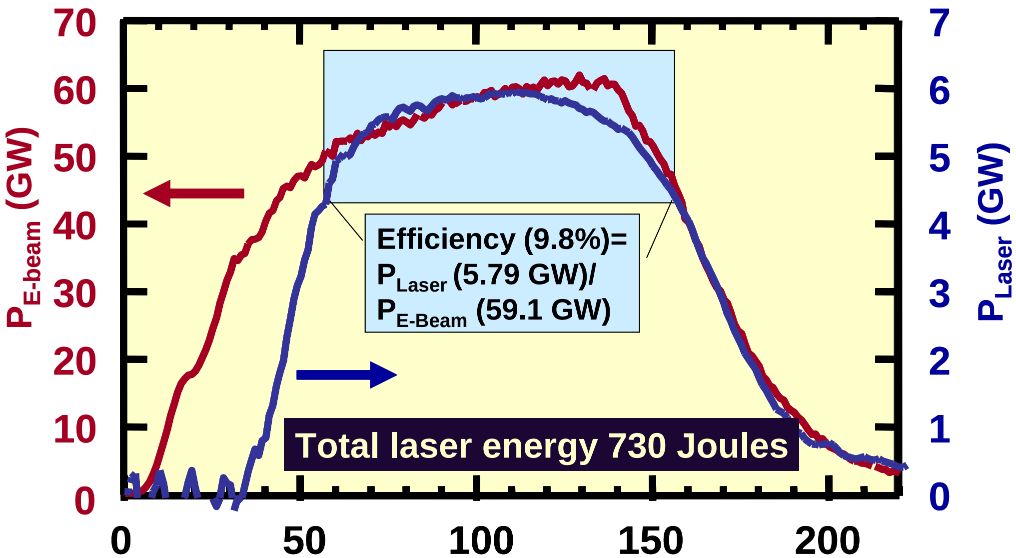
Shortest wavelength (248 nm)
maximizes absorption & rocket efficiency
minimizes risk from Laser Plasma Instabilities (LPI)

Should be durable and robust:
gas laser, driven by industrial based pulsed power
Commercial discharge systems go > 10^9 shots

Major accomplishments:
80 - 710 J/pulse in repetitive operation at 1-5 Hz
Predict > 7% efficiency based on R&D of the individual components

KrF lasers would be well suited for the less strenuous HEDLP application

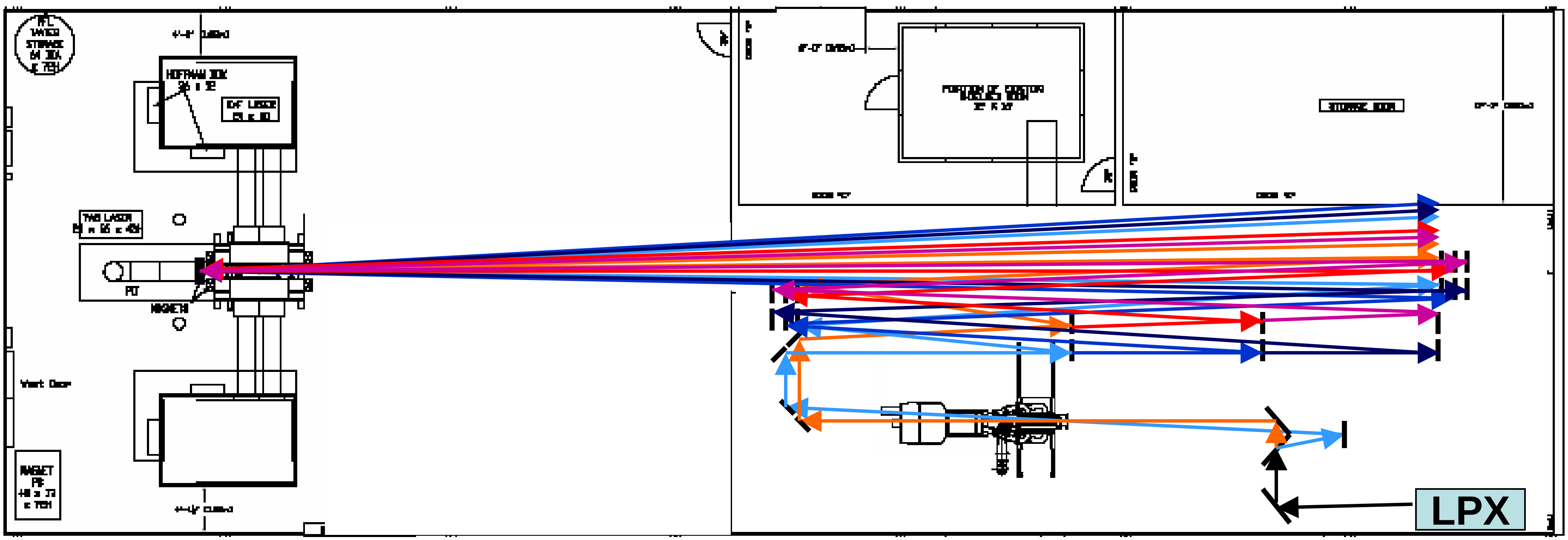
Based on Electra R&D, we predict an overall wall plug laser efficiency of > 7 %



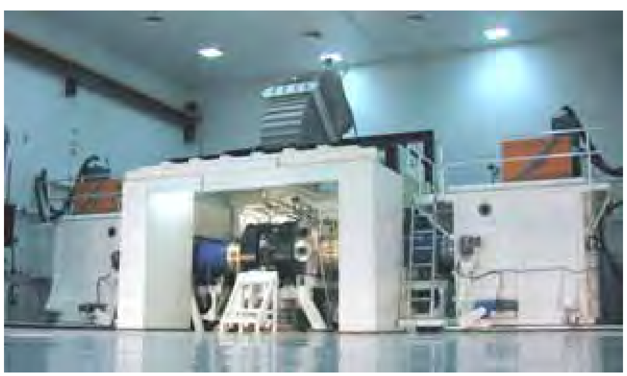
Pulsed Power	Advanced Switch	82%
Hibachi Structure	No Anode, Pattern Beam	80%
KrF	Based on Electra exp'ts	12%
Optical train to target	Estimate	95%
Ancillaries	Pumps, recirculator	95%
Total		7.1%

The Electra Laser Facility

NRL Laser Fusion



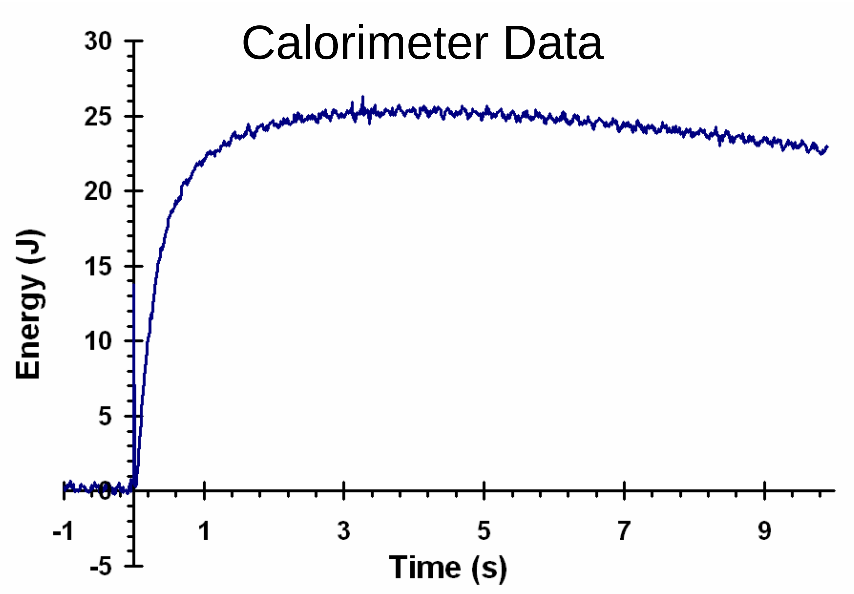
Main AMP

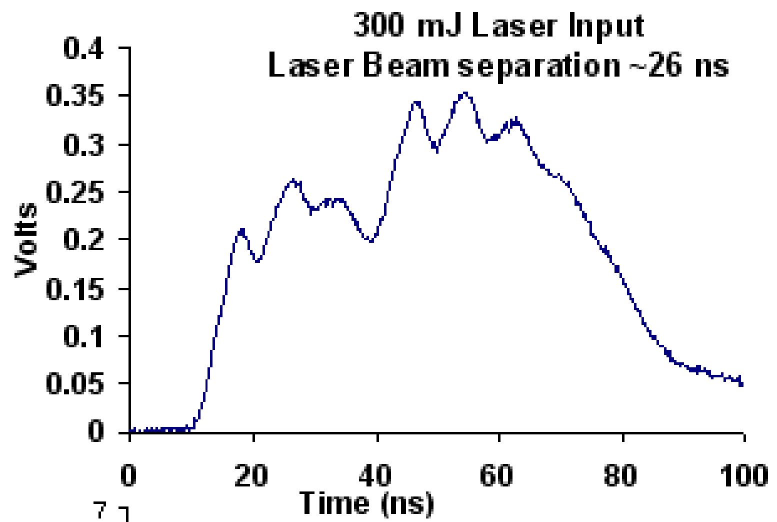


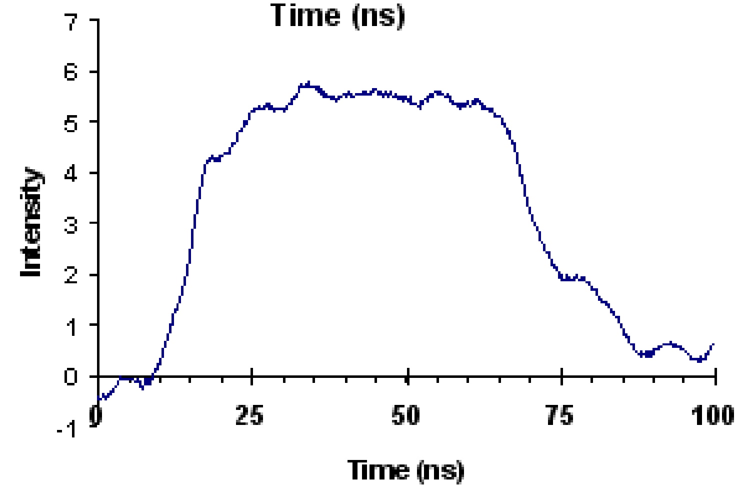
Pre-AMP

First results (4/11/07)
Two angularly multiplexed beams through preamp.
25 J total

NRL Laser Fusion





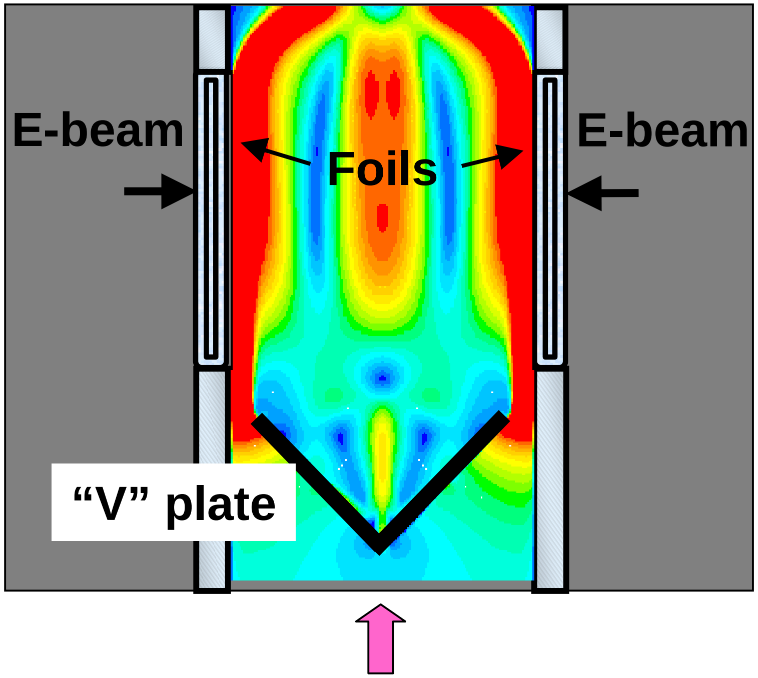


25 J Laser Output

We have three options to keep the foil cool

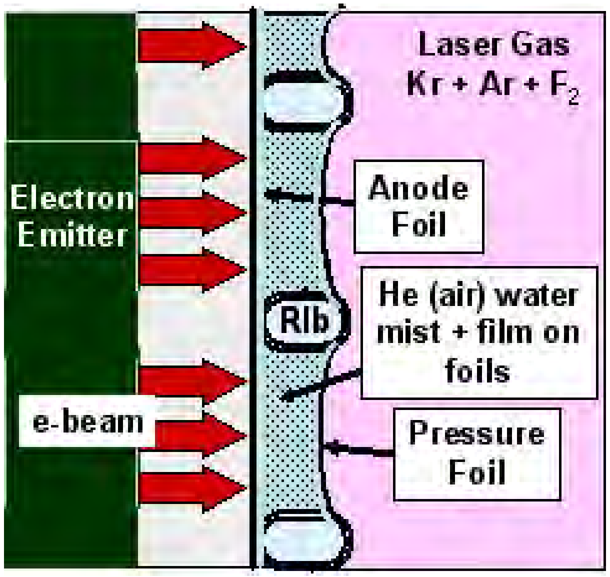
1. "V" plate

Foil Temp = 220 °C
@ 2.5 Hz, 700 J cathode
Predict 440 °C @ 5 Hz
~ 75% Long term fatigue limit of SS



2. "Mist Cooling"

Foil Temp < 140 °C
@ 5 Hz, 10 k + 5 k + 5 k shots
Tested in module, and full size



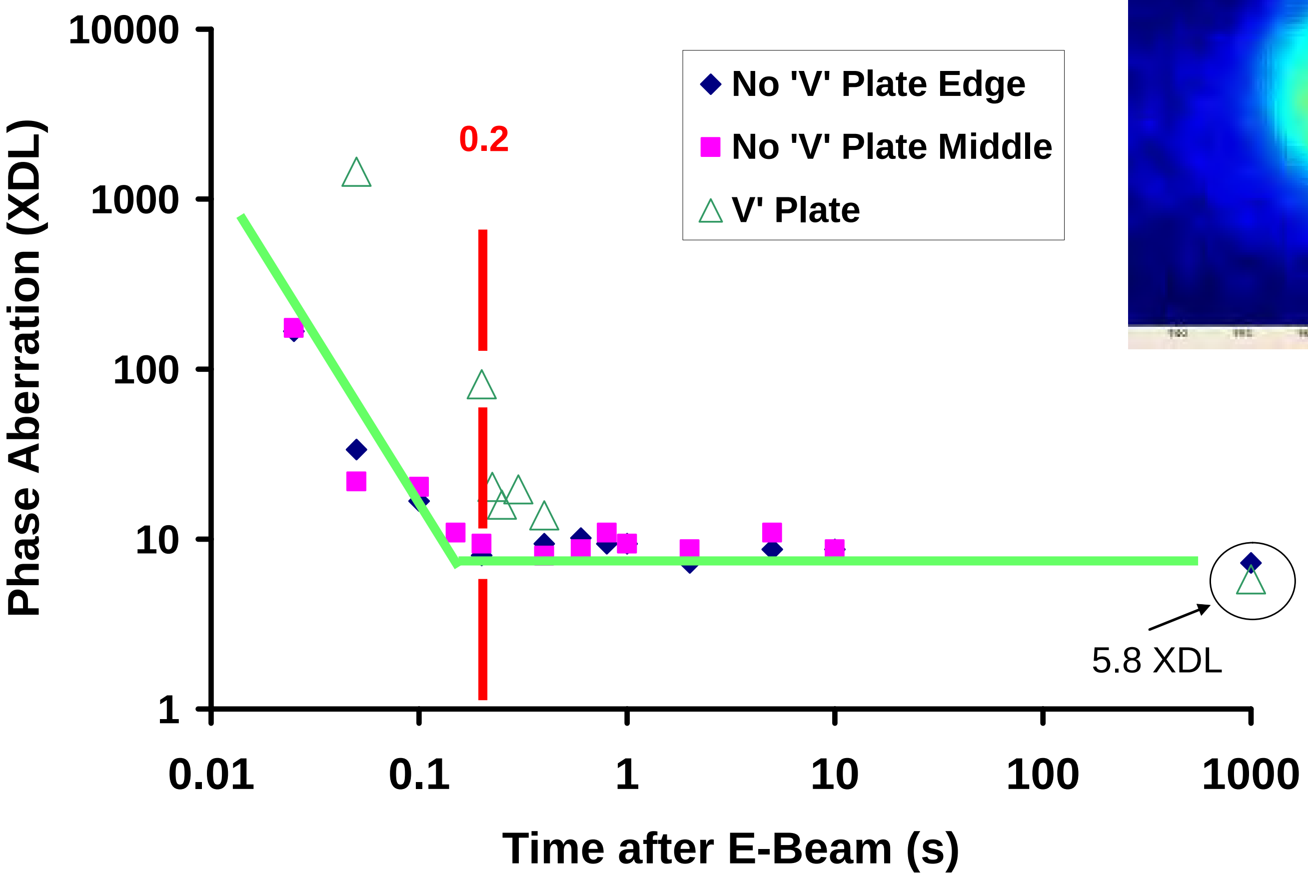
3. "Gas Injection"

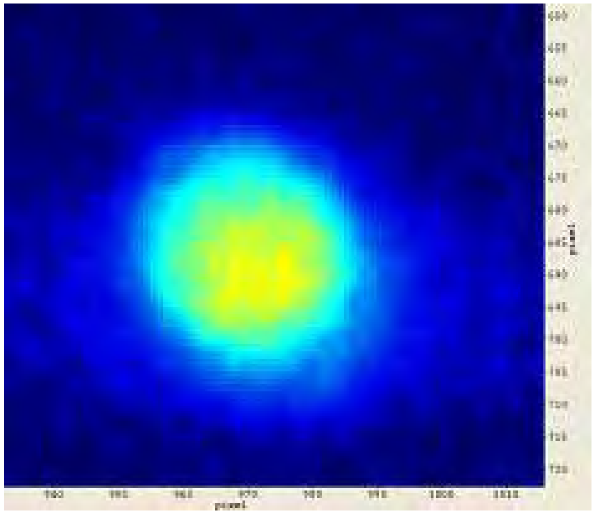
Under development, test 5/07

2 & 3 developed by Georgia Institute of Technology

Phase aberration studies suggest laser gas “recovers” within 200 msec (5 Hz)

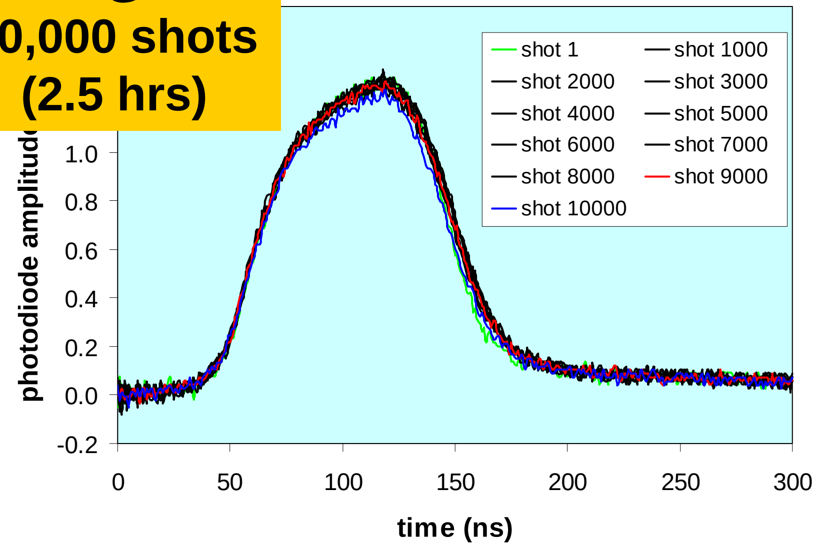
NRL Laser Fusion



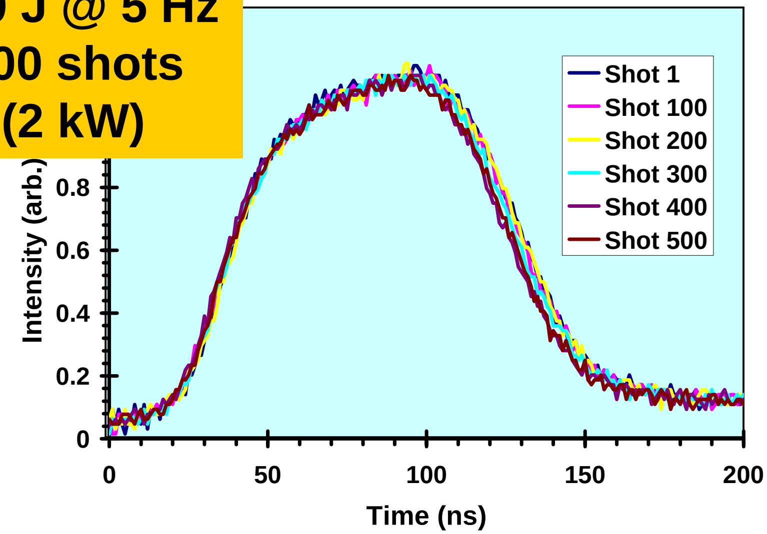


Electra laser is very consistent output during long duration runs:

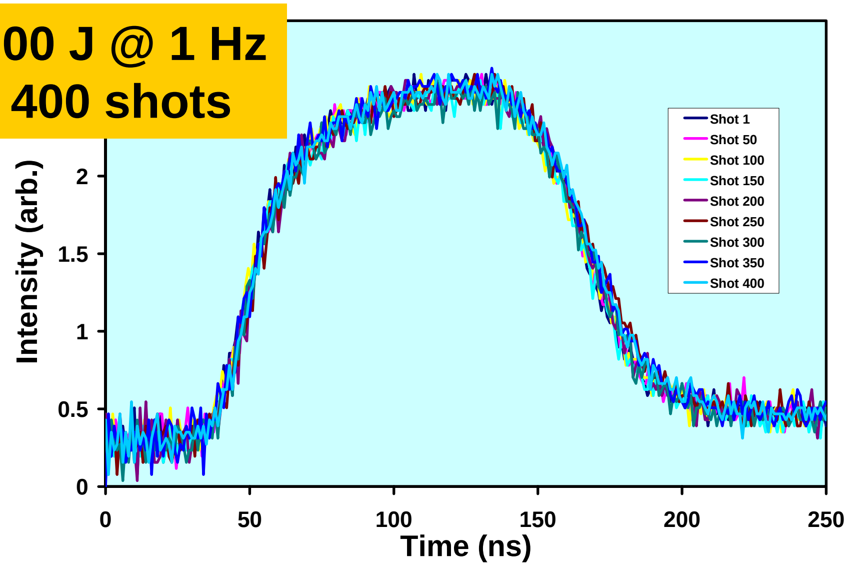
300 J @ 1 Hz
10,000 shots
(2.5 hrs)



400 J @ 5 Hz
500 shots
(2 kW)



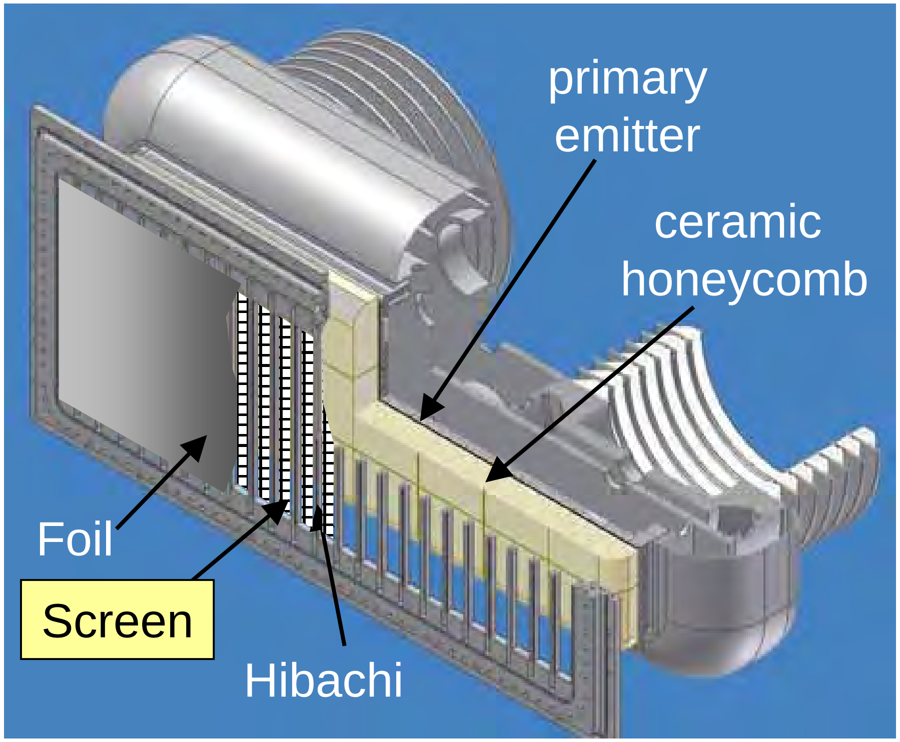
700 J @ 1 Hz
400 shots



Also:
80J, @ 2.5 HZ
25,000

Currently, long runs terminated by small hole in hibachi foil. Foils are *not* failing due to global thermal management

Caused by cathode debris/hot spots, correlated with pulsed power misfires



Solutions: SHORT TERM

Better control of pulsed power

LONG TERM

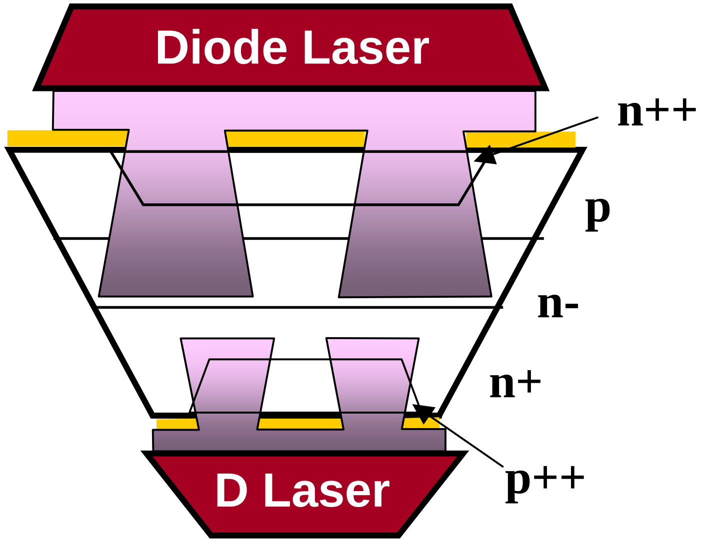
All solid state pulsed power

More durable cathodes

Solid State Pulsed Power….
Baseline approach:"Laser Gated Pumped Thyristor (LGPT)
The principal has been demonstrated

CONCEPT

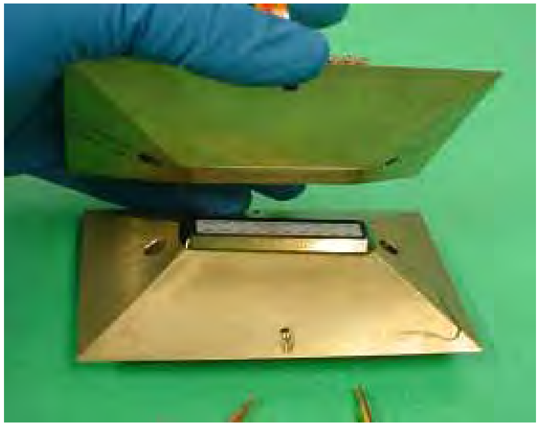
- Diode lasers flood thyristor with photons
- Ultra fast switching times (< 100 nsec)
- Continuous laser pumping reduces losses



PROGRESS

- > 15 M shots, 5-7 Hz
- 16.4 kV
- 2.0 kA/cm^2
- > 80 kA/μsec

(meets specs)

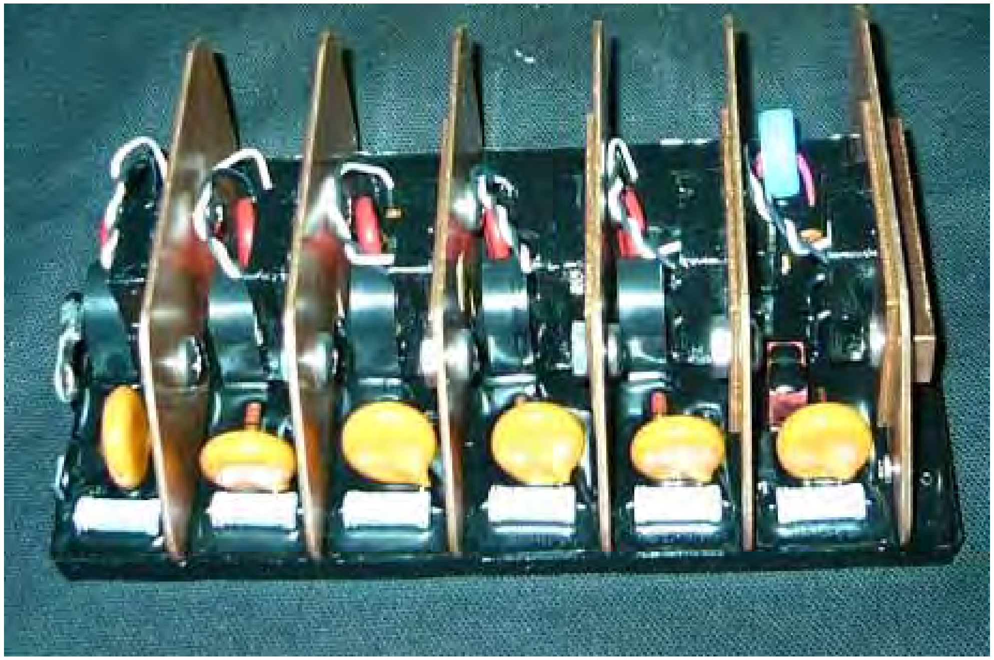


L3 communications Applied Technologies Pulse Sciences

OPTISWITCH

Existing all electric thyristors with "saturating magnetic assist" may be a lower cost alternative

S33 Solid State (45 kV) Switch
Applied Pulsed Power, Ithaca, NY



33 Specifications:
30 kA/usec
> 10^9 shots
< $4 k each

Bench tested to 50 kA/usec

PLEX LLC has demonstrated
96 kA/usec @ 40 kV with SMA

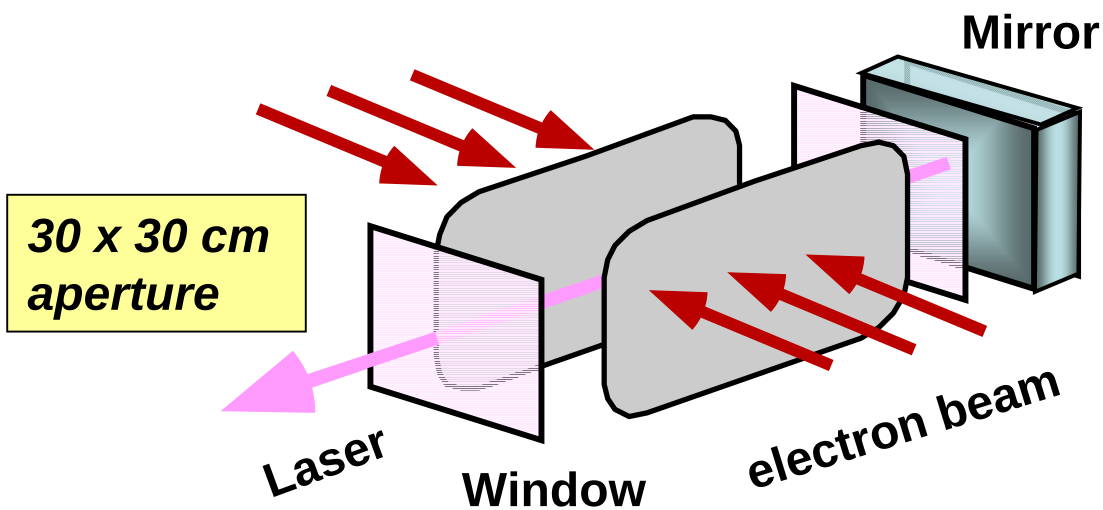
PLEX LLC has designed a new
type of Marx that requires lower
dI/dt. We will build a test system

PLEX LLC

We will retrofit Pre-Amplifier with solid state switches (conventional S 33 thyristors *-or-* SMA + S33 thyristors)

The next step: build a 1-2 kJ Laser Amplifier to be used as input amplifier to 30 kJ FTF Main amp

PROVISIONAL, we expect to finalize the design within the next 2 years



E-beam Voltage:	500 kV
E-beam total current:	180 kA
Aperture:	30 x 30
Gain length	100 cm
Pump (78% hibachi):	780 kW/cc
Deposited energy:	15.8 kJ
Laser Output	1.9 kJ
Intrinsic Efficiency	12.0%

Two electron-beams:
500 keV, 90 kA, 225 nsec
30 cm x 100 cm each beam

Short term (< 2 years) goals of KrF Laser development program

NRL Laser Fusion

Turn into full Laser System (5 Hz, > 700 J, > 10 k runs)
- Seed laser + Pre-amplifier + Main Amplifier
- Angular multiplexing,
- without ISI, then with ISI (may require additional stage)

Demonstrate durability of foil/cathode on main amplifier
- ~ 100 k shots continuous, > 700 J/pulse, 5 Hz, req'd focal profile

Pulse shaping experiments (on Nike)
- Pockels cells
- Evaluate Kerr Cell option

Identify F_2 resistant window/coating

Solid State Pulsed Power Development
- Develop solid state switch
- Retrofit Pre-Amplifier, demonstrate system
- Build Cathode tester (long pulse, rep-rate)

Complete Conceptual Design for 2 kJ, 5 Hz driver amplifier for FTF Phase Ia

Long term (> 2 years) goals of KrF Laser development program

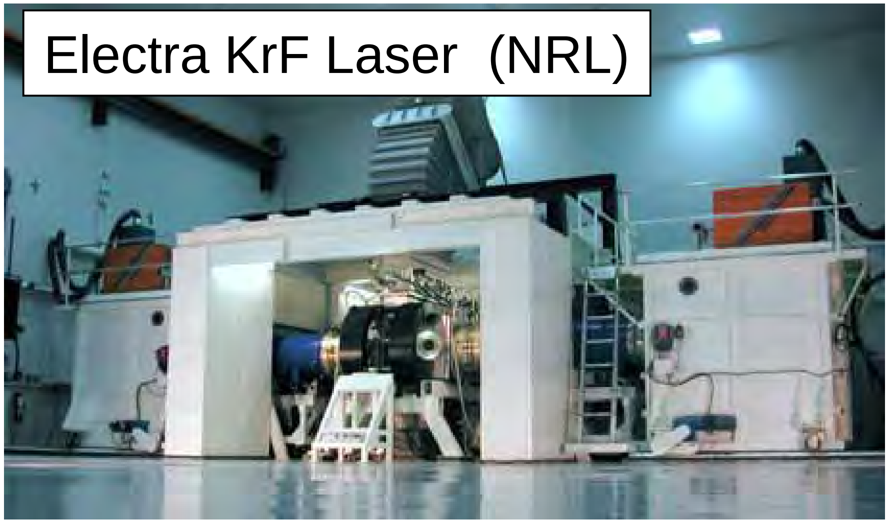
See Steve Obenschain talk on the FTF

BACKUPS

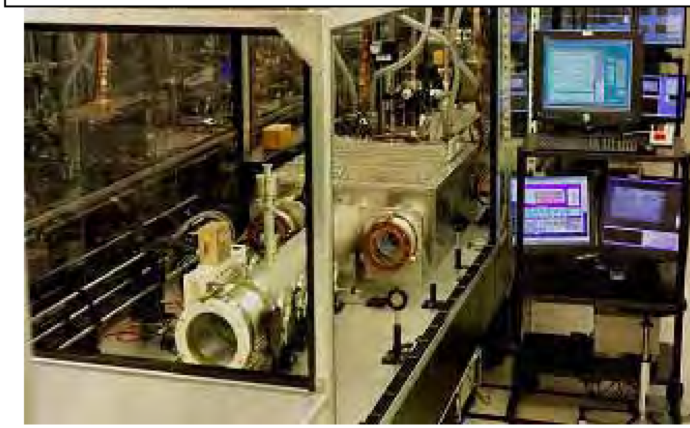
The HAPL program is developing two lasers:

- ♦ **Diode Pumped Solid State Laser (DPPSL)**
- ♦ **Electron beam pumped Krypton Fluoride Laser (KrF)**

Electra KrF Laser (NRL)



Mercury DPPSL Laser (LLNL)

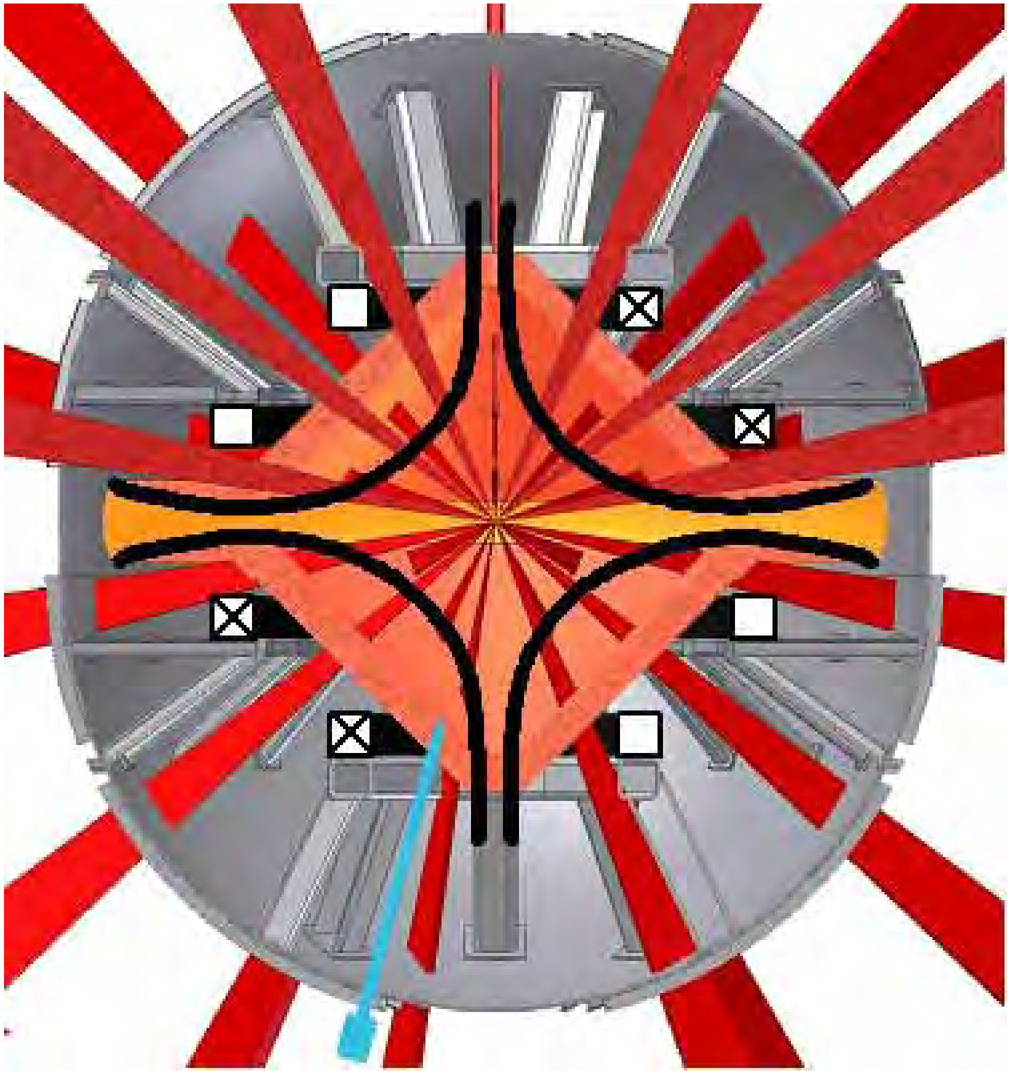


300-700 J @ 248 nm
120 nsec pulse
1 - 5 Hz
25 k shots continuous at 2.5 Hz
Predict 7% efficiency

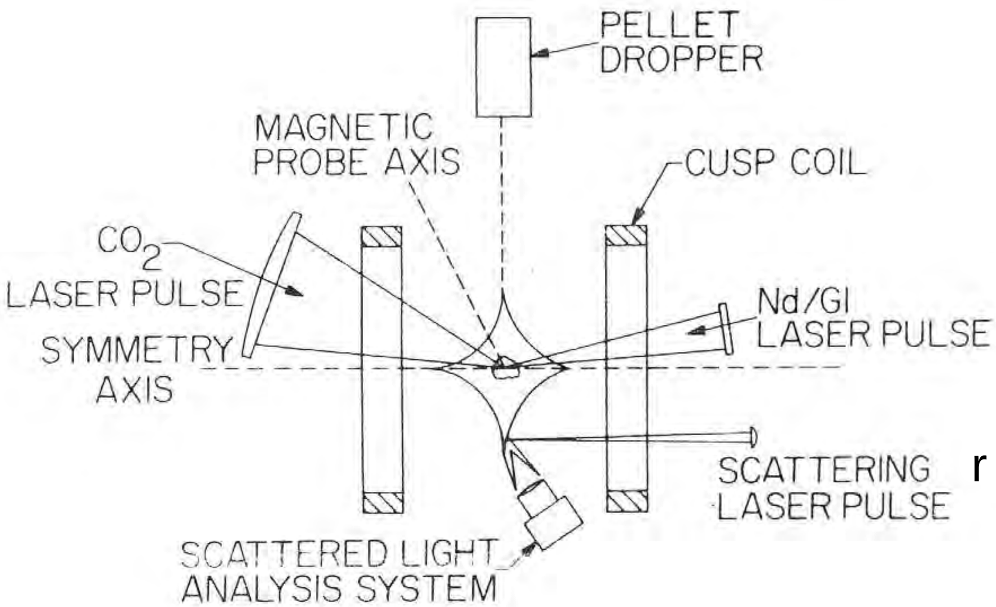
55 J @ 1051 nm*
15 nsec pulse
10 Hz
100 k shots continuous @ 10 Hz
* Recently demo 73% conversion at 2ω

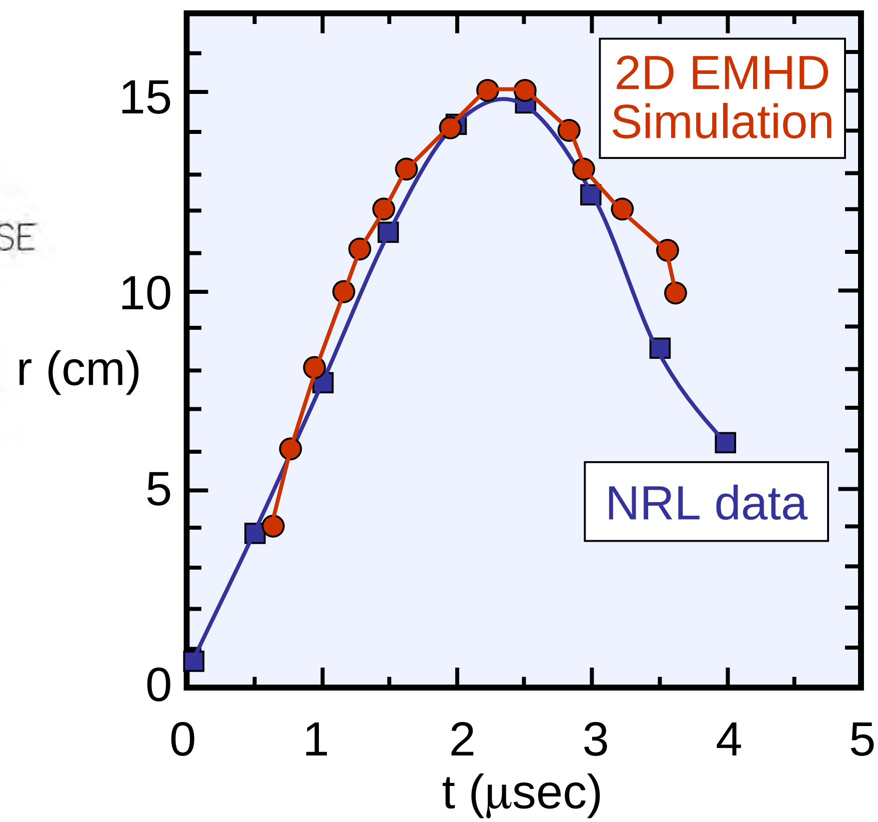
"Magnetic Intervention" offers a way to keep the ions off the wall

1. Cusp Field (1 T = 10 kG) imposed on chamber
2. Ions radially "push" field until stopped by magnetic pressure
3. Moving field resistively dissipated in first wall/ blanket
4. Ions, at reduced energy *and power,* escape cusp and absorbed in dump
5. Allows SiC wall, which means higher temperature blanket



♦1979 NRL experiment showed principal of MI.
♦ Recent simulations predict plasma & ion motion

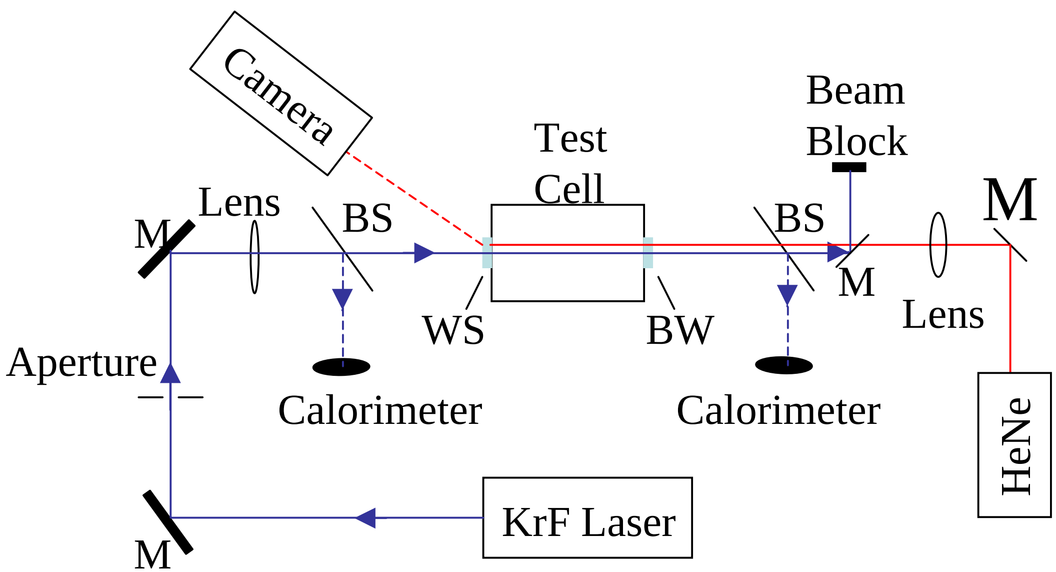




*R. E. Pechacek, *et al*., Phys. Rev. Lett. **45**, 256 (1980).

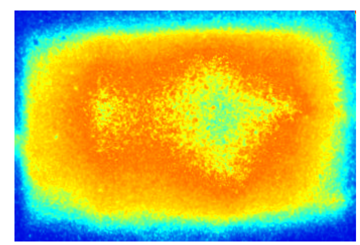
NRL
A.E. Robson
Voss Scientific

Apparatus for testing/evaluating fluorine resistant, high damage threshold, high transparency windows

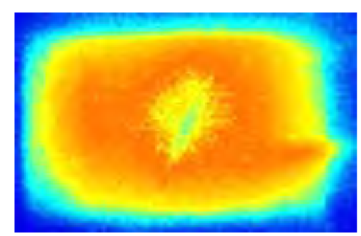


Beam flat top uniform to within 10%

Profile 8 x 3.8 mm^2 spot
1 J/cm^2 fluence



Profile 6 x 3 mm^2 spot
2 J/cm^2 fluence



Summary of window tests

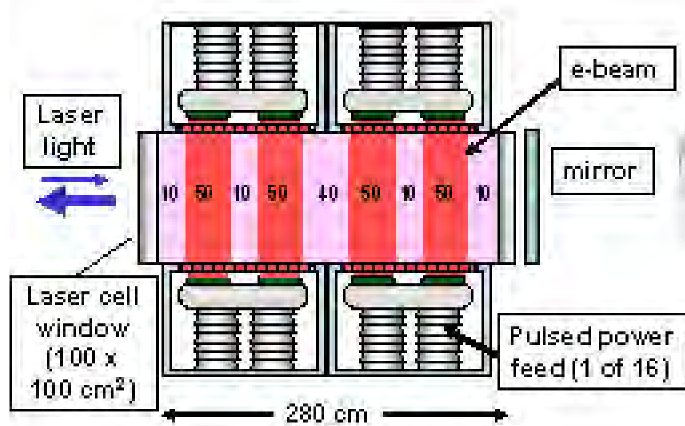
1 J/cm^2, 0.3% F_2

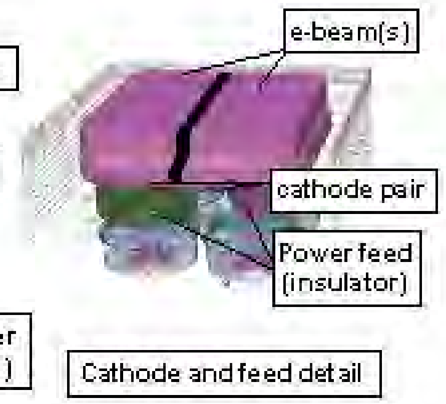
Material	Reflectivity	Summary
Uncoated fused silica	4%	Degrade < 100 k shots Vendor dependent
4 Layer Coated fused silica ½λ NdF_3/ ¼λ MgF_2 / ¼λ NdF_3/ ¼λ MgF_2	< 1%	Degrade ~ 60 k shots Substrate. Not coating
Uncoated CaF_2	3.6%	No degrade > 180 k shots (Commercial > 10^9 shots)
Uncoated MgF_2	2.5%	No degrade > 180 k shots (Commercial > 10^9 shots)

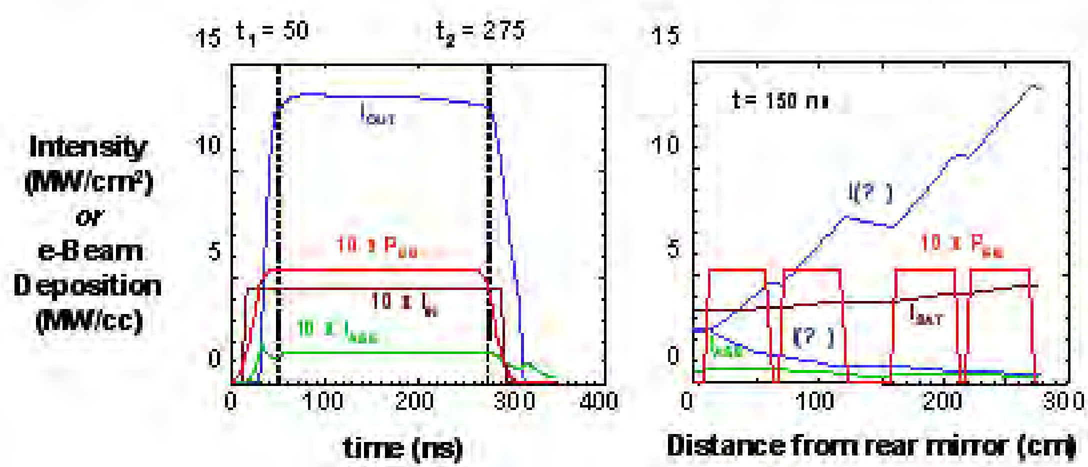
PLANS: 4 layer on CaF_2
New Teflon coating on quartz developed by Schaffer

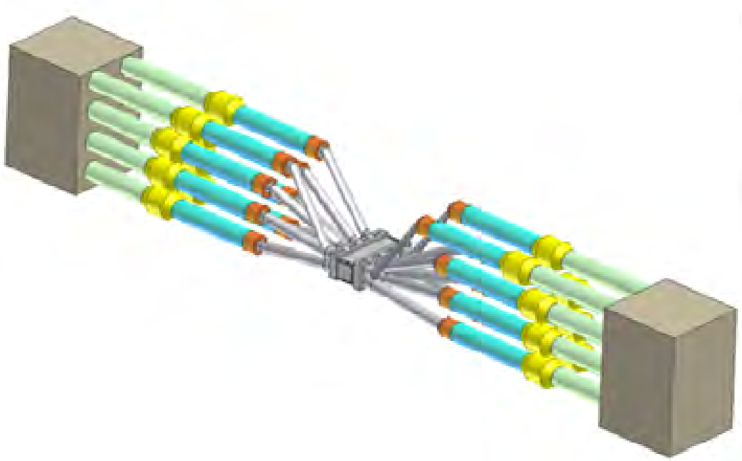
The 30 kJ FTF Main amp

E-beam Voltage:	800 kV
E-beam total current:	1600 kA
Aperture:	100 x 100
Gain length	200 cm
Pump (84% hibachi):	538 kW/cc
Pulse length	225 nsec
Deposited energy:	238 kJ
Laser Output	30.1 kJ
Intrinsic Efficiency	12.7%







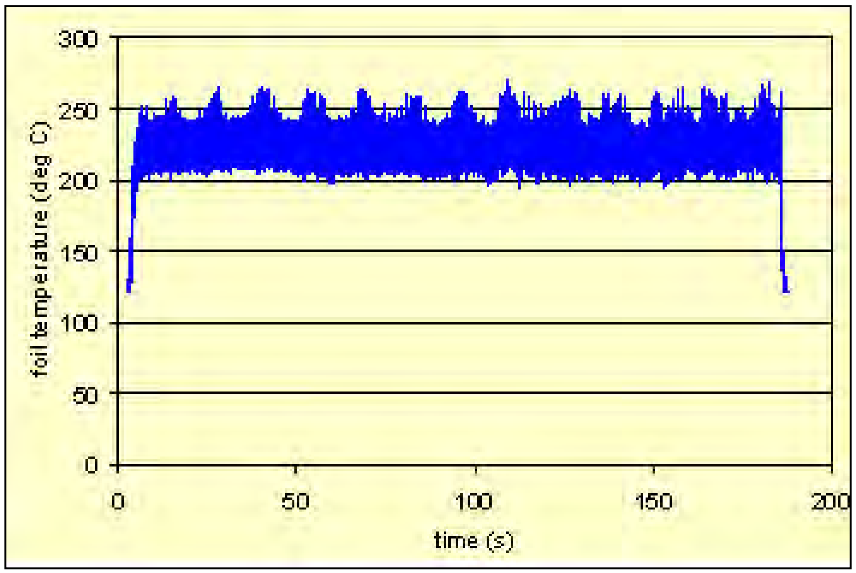


Foil temperature does not limit the laser run duration

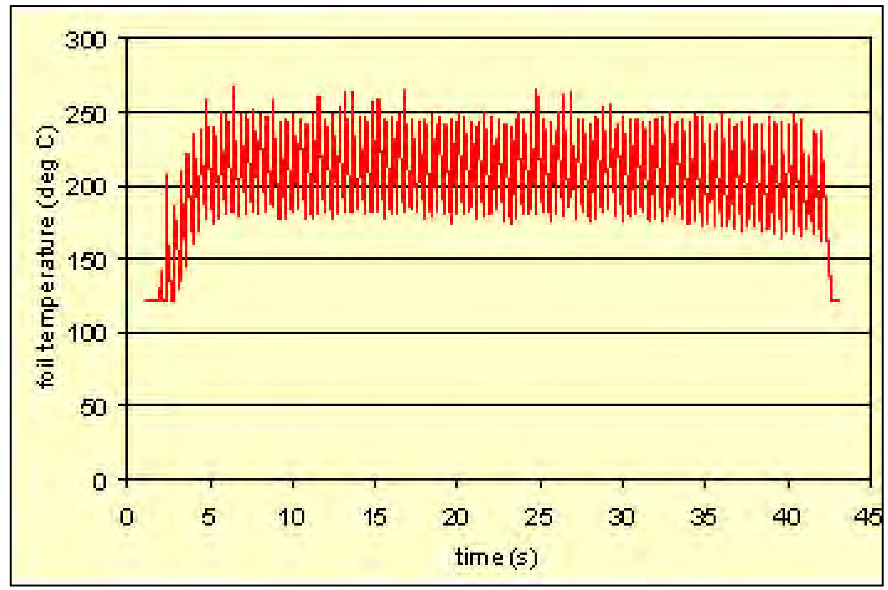
Hibachi foils are cooled by forced convection with the laser gas

Laser gas included 9% of He for enhanced cooling (10% effect)

5 Hz
monolithic cathode



2.5 Hz
strip cathode



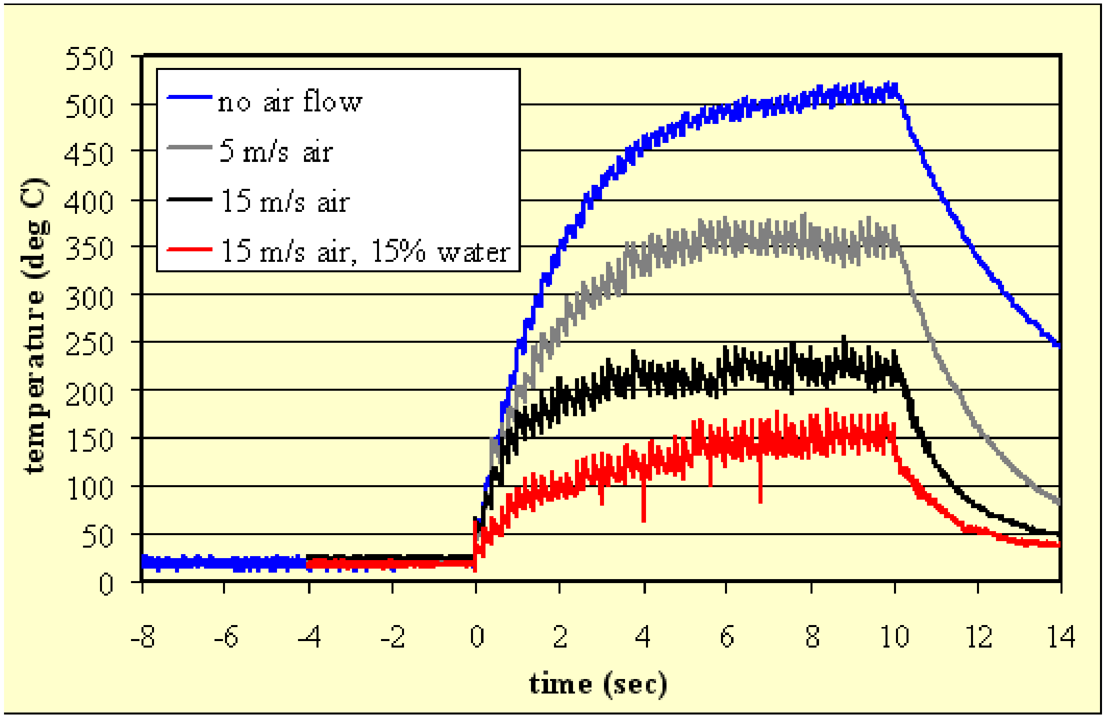
Expect a foil temperature of less than 500°C at 5 Hz with a strip cathode

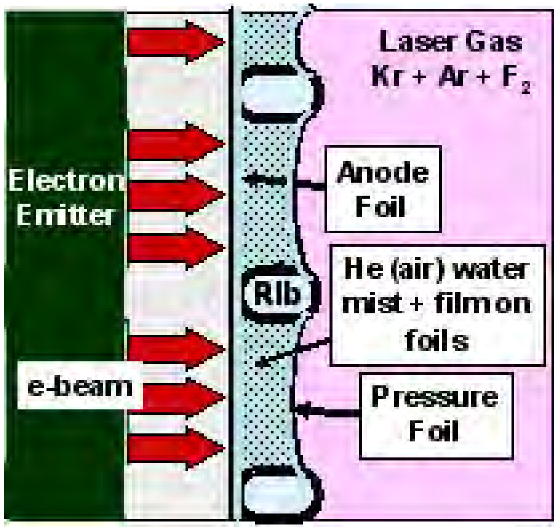
The foil heat load of the strip cathode is approximately twice the heat load produced by the monolithic cathode (for the same rep-rate)

Alternate foil cooling concept: Mist cooling

Demonstrated consecutive runs of 10k, 5k, and 5k all continuous @ 5 Hz

Foil temperature (1 mil Ti @ 5 Hz)





(developed by Georgia Tech)

Pro: Successful demonstration on subscale module @ 5 Hz (foil temp < 140°C)

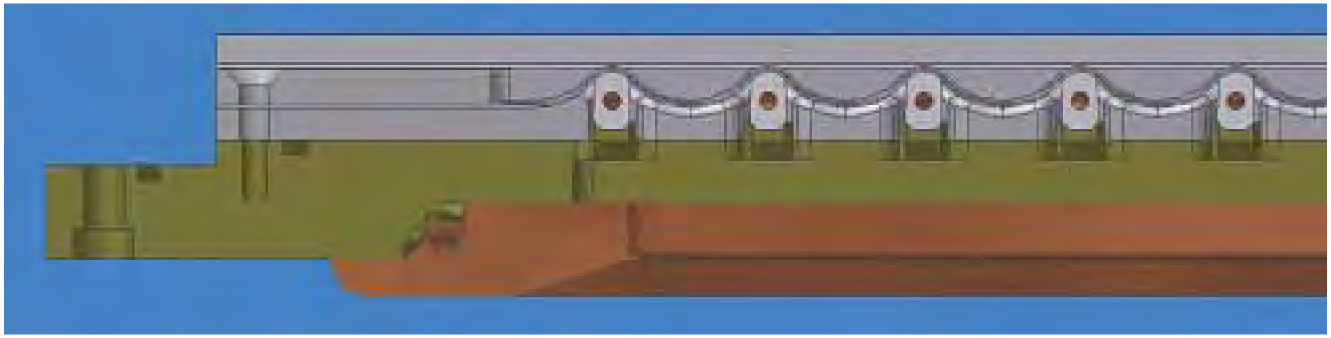
Con: More complex, lower overall efficiency (reduced by ~15%)

Full size hibachi test are scheduled in Fall 2006

Scalloped hibachi significantly reduces the stress of the foil

Fatigue strength of 304 stainless steel

						stress/yield (long term fatigue)			
						100ºC		480ºC	
t = thick	Rib spacing (cm)	a 1/2 Rib spacing (in)	Rib width (in)	θ *(deg)*	**Applied Stress (psi)**	**Allowed Stress (psi)**	**Ratio**	**Allowed Stress (psi)**	**Ratio**
0.001	3.40	0.669	0.390	5	**230378**	**83300**	**2.77**	**59800**	**3.85**
0.001	3.40	0.669	0.390	10	**115629**	**83300**	**1.39**	**59800**	**1.93**
0.001	3.40	0.669	0.390	40	**31237**	**83300**	**0.37**	**36000**	**0.87**
0.001	3.40	0.669	0.300	45	**28396**	**83300**	**0.34**	**36000**	**0.79**
0.001	3.40	0.669	0.300	50	**26211**	**83300**	**0.31**	**36000**	**0.73**



Scalloped hibachi

When complete, we will have a complete FTF beam line through the driver amplifier

Sequence of events:

1) Build single pulsed power system (solid state switches)
    Demo 1 M shots @ 5 Hz

2) Couple pulse power system into gas cell (no F_2)
    Use as existing Electra components
        magnet, gas recirculator, hibachi thermal management
    Demo 1 M shots @ 5 Hz

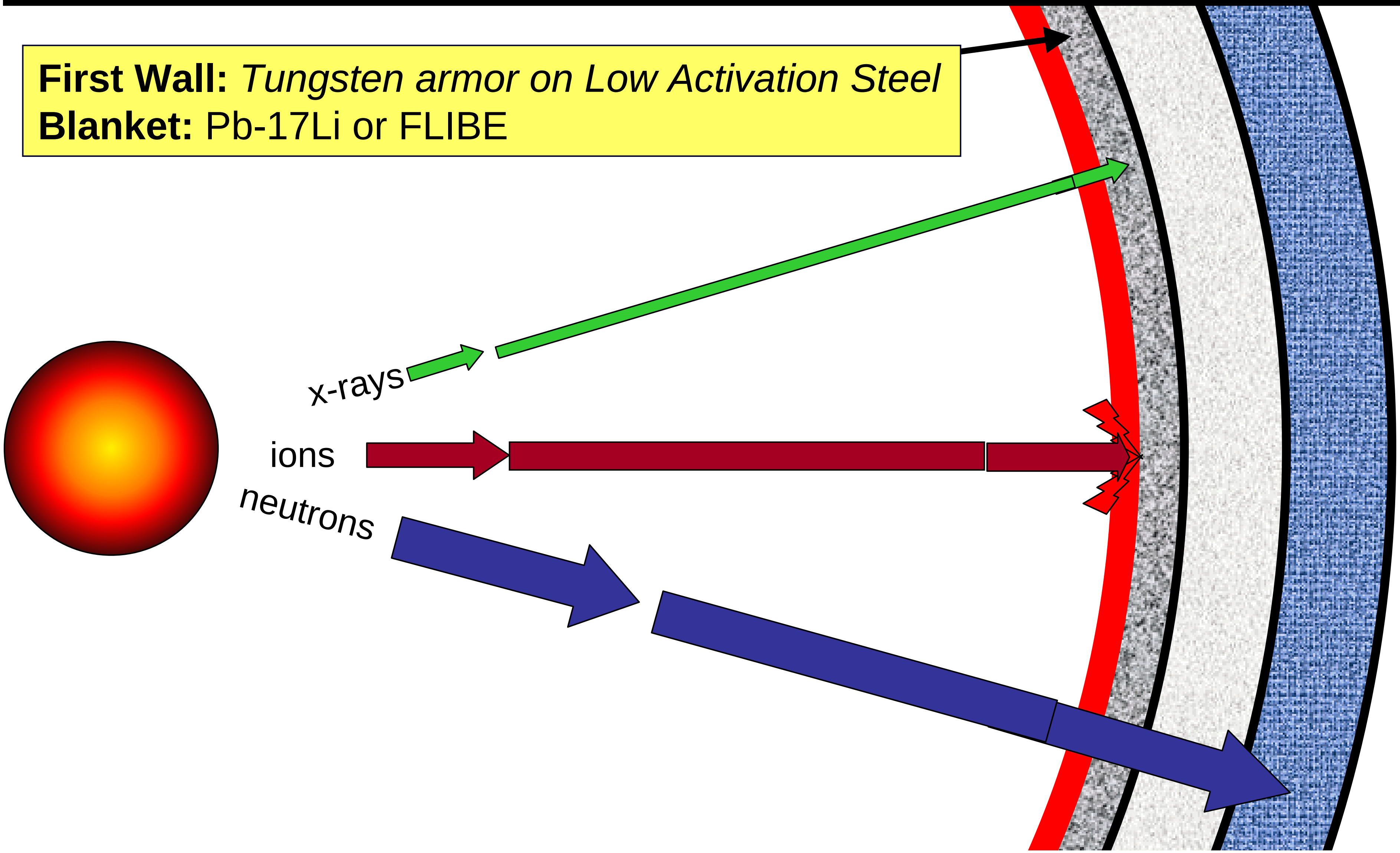
3) Turn into laser amplifier
    Build second pulsed power & e-beam components
    Install windows and F_2 handling
    Feed with existing Electra pre-amplifier

    2.5 nsec pulses, only a few multiplexed beams

4) Demonstrate the entire system for >1 M shots @ 5 Hz

The first wall of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.

First Wall: *Tungsten armor on Low Activation Steel*
Blanket: Pb-17Li or FLIBE



UCRL-PRES-230251

New Concepts for Reducing Costs and Increasing Efficiency of Solid-State Laser Drivers for IFE

Inertial Fusion Energy Science and Technology

Strategic Planning Workshop

San Ramon, California

April 24, 2007

A. Erlandson, E. Ault, C. Barty, A. Bayramian, R. Beach, R. Campbell, R. Cross, C. Ebbers, T. Ladran, Z. Liao, J. Murray, R. Page, K. Schaffers, T. Soules, S. Sutton, S. Telford, and J. Caird

Photon Science and Applications Program

National Ignition Facility Programs Directorate

Lawrence Livermore National Laboratory

This work was performed under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Studies are underway at LLNL to develop low cost, high-efficiency laser drivers

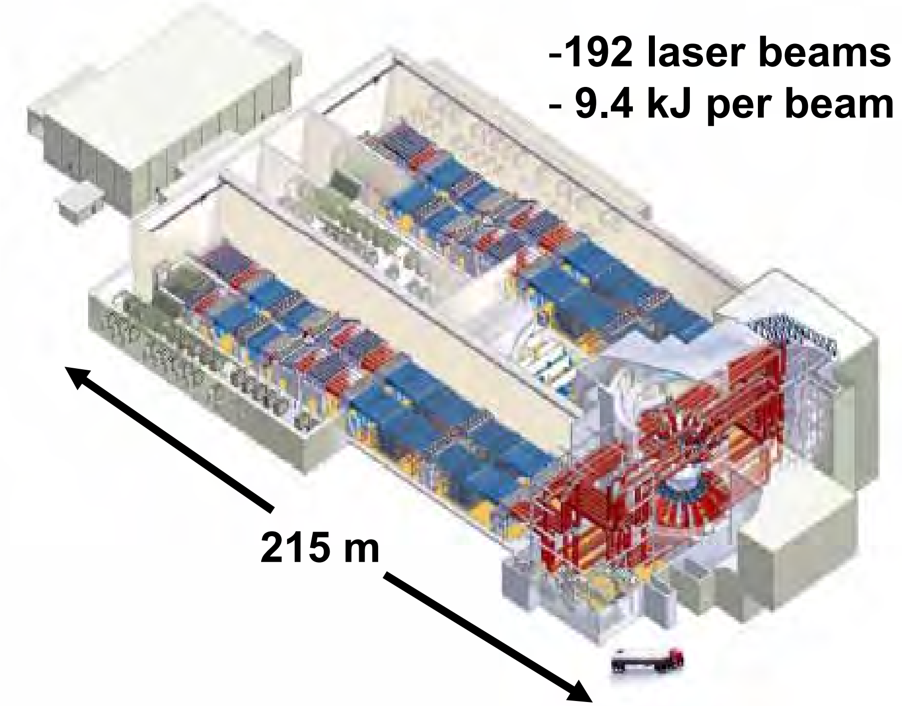
• Our work builds upon experience with large flashlamp-pumped laser systems and smaller diode-pumped systems
  - NIF, Mercury and SSHCL

• We have concentrated first on opening up the design space
  - application of developing technologies
  - blue-sky ideas

• Significant reductions in costs and increases in efficiency appear feasible
  - only tens of beamlines
  - > 20% efficiency

• We plan to undertake more detailed performance calculations and design development in coming months

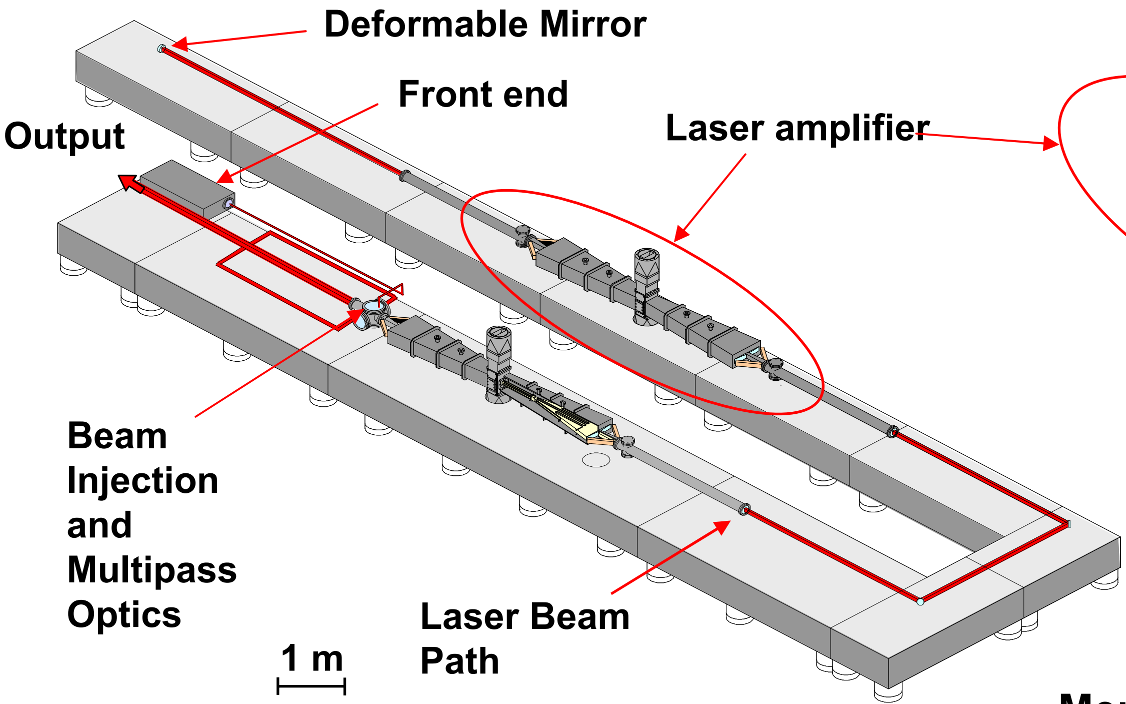
NIF's driver laser will produce 1.8 MJ and is comparable to IFE lasers in output energy



	NIF	IFE Laser
Energy	1.8 MJ	2 MJ
Wavelength	0.35 μm	0.5 μm
Wall-plug efficiency	0.75%	> 5%
Repetition rate	1 shot / 2 hours	5 Hz
Cost	~ $500 / J	< $500 /J

- NIF uses passively-cooled, flashlamp-pumped laser slabs
- Solid-state IFE lasers use diode-pumped, actively-cooled slabs to meet efficiency and repetition rate requirements
- Nonetheless, NIF provides much useful information to designers
  - costs, learning curves, and "lessons learned"
  - importance of using optics that have good manufacturing characteristics
  - analysis tools, work-breakdown structure, requirements documents

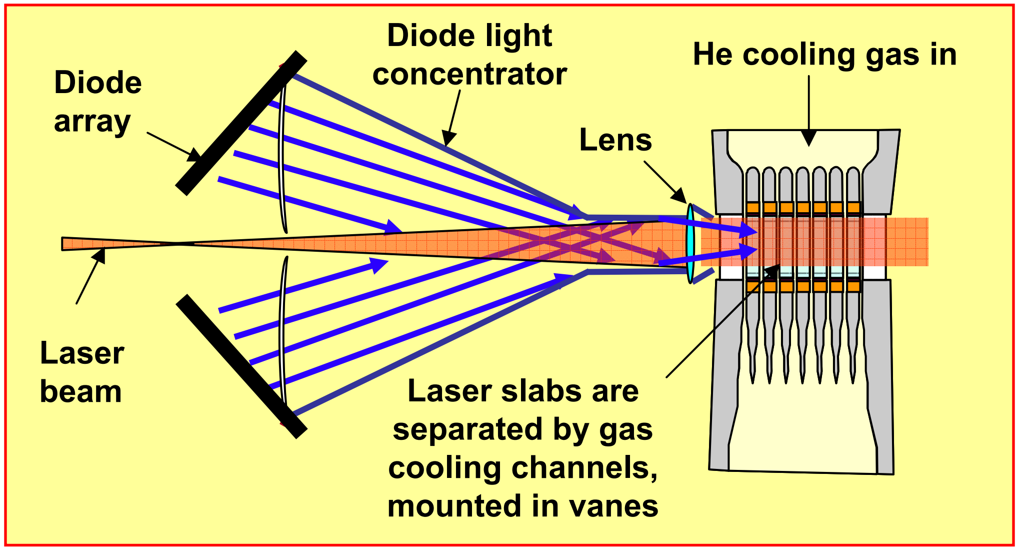
Mercury is a test-bed for developing high-average-power diode-pumped solid-state laser technology for IFE



	Goals	Status
Energy (J) (@ 1 ω)	100	65
Optical Efficiency (%)	10	6.5
PRF (Hz)	10	10 Hz
Pulse length (ns)	3-10	14
Wavelength (μm)	0.52 / 0.35	0.52
Bandwidth GHz	>150	In Process
Beam quality (xDL)	5	4

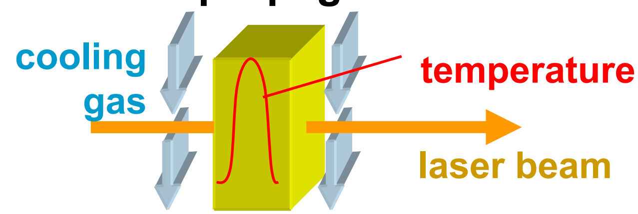
- Mercury addresses issues important to IFE drivers:
  - high-power laser diodes
  - thermal management for optics
  - optics lifetime
  - growth of Yb:S-FAP, a high-gain slab material

Mercury's amplifiers use several component technologies developed at LLNL



Gas-cooled slabs

- Pumping processes heat laser slabs so laser slabs must be cooled
- Cooling slab faces produces little wavefront distortion since temperature gradients are parallel to the beam propagation direction

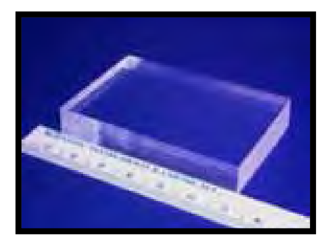


Diode arrays (2001)

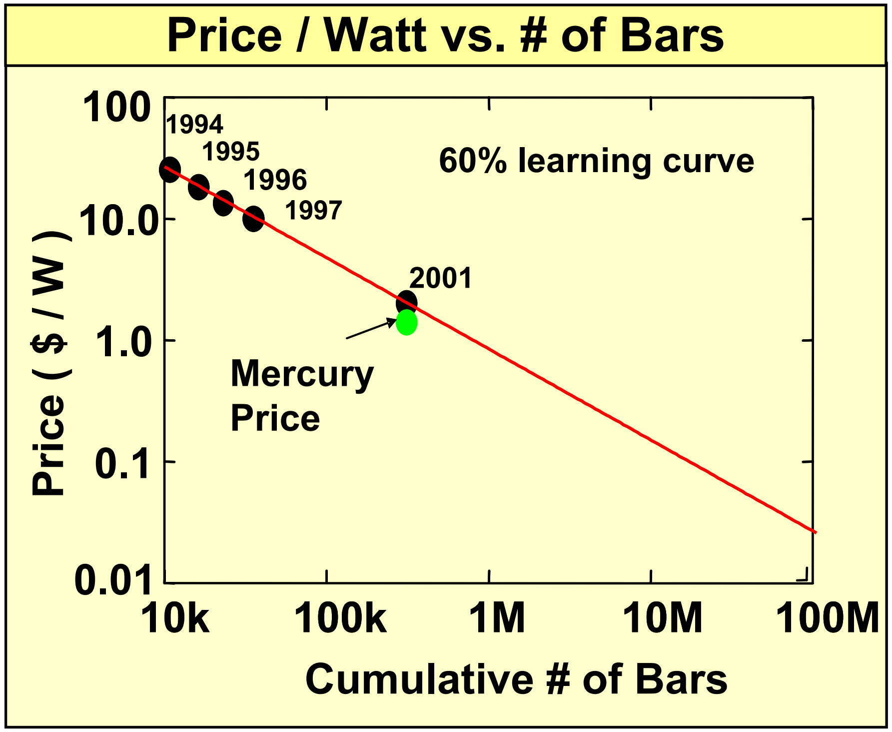
- Each array emits 80 kW peak optical power
  - 800 bars x 100 W / bar
  - 900 nm
- Electrical-to-optical conversion efficiency is 45%

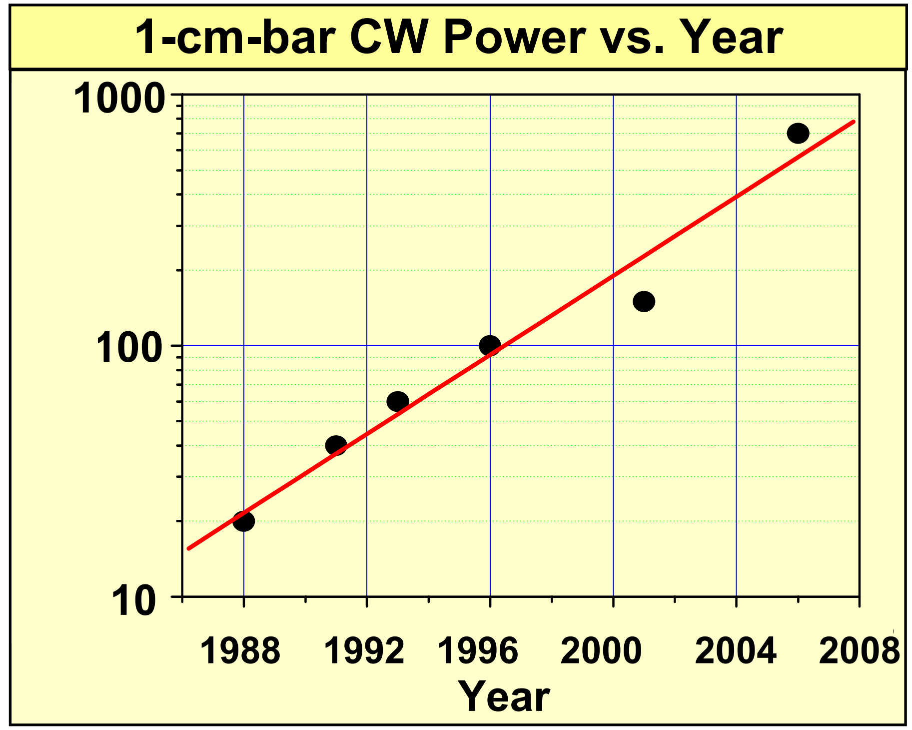
Yb:S-FAP slabs

- High-gain material with ~1-ms storage lifetime
  - needs only ~ 1/3 as many diodes as Nd^{3+} lasers



Diodes are becoming cheaper, more powerful, and more efficient

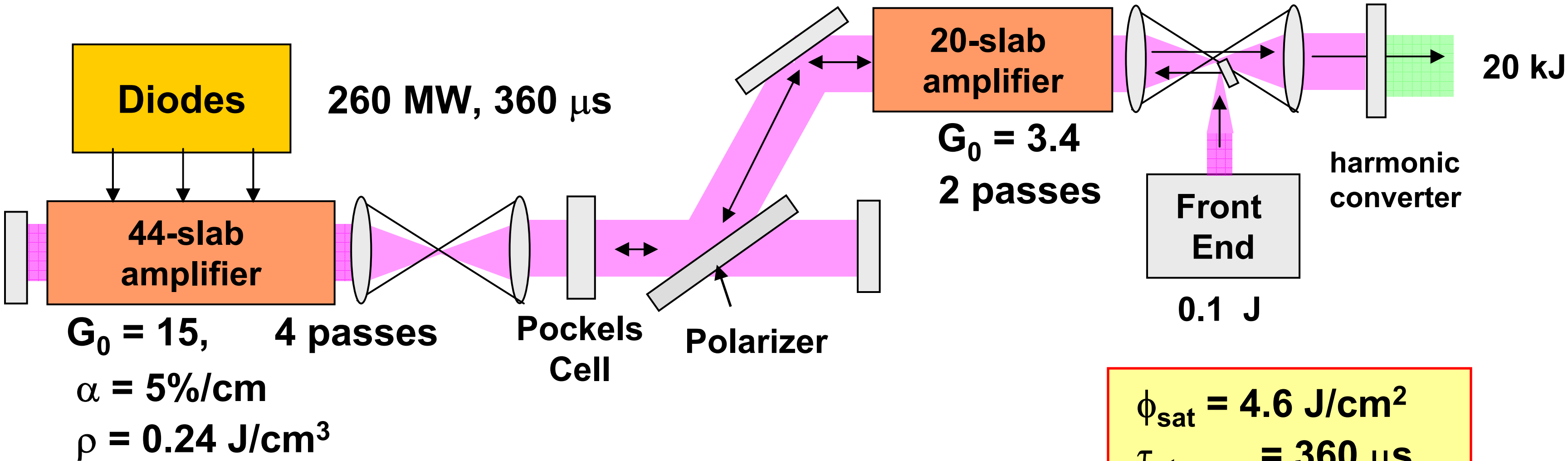




- Several companies supported by the DARPA Super-High-Efficiency Diode Sources (SHEDS) Program have developed diodes with electrical-to-optical efficiency > 70%

- Goal of quantum-dot diode program at the University of Central Florida is > 90% efficiency

Nd:glass laser with NIF-like design is a viable low-risk option – when diodes are cheap

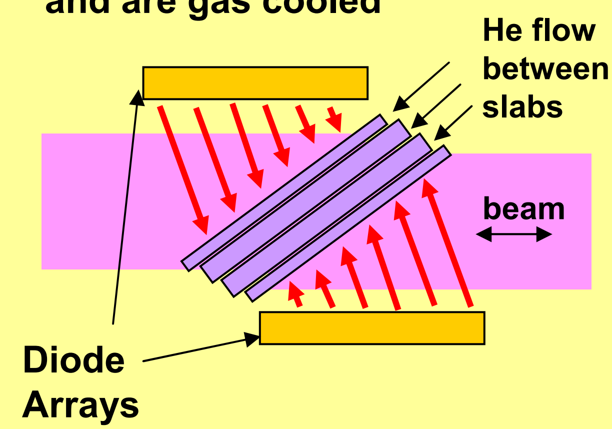


ϕ_{sat} = 4.6 J/cm^2
$\tau_{storage}$ = 360 μs

- 20 kJ / beamline requires high-damage-threshold optics
- Overall wall-plug efficiency ~ 13%
- 100 beamlines are needed for a 2-MJ laser

	Diode costs	
Unit costs	@10¢ / W	@1¢ / W
20-kJ beamline	\$26 M	\$2.6 M
2-MJ system	\$2.6 B	\$260 M

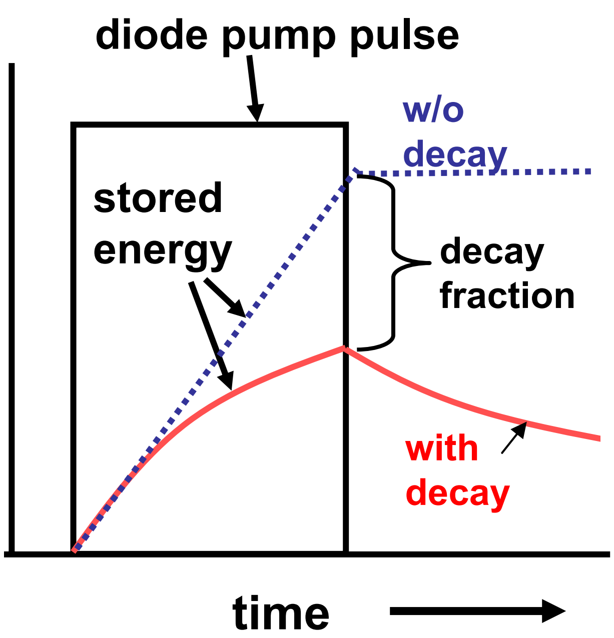
Brewster-angle slabs are stacked in groups of four and are gas cooled



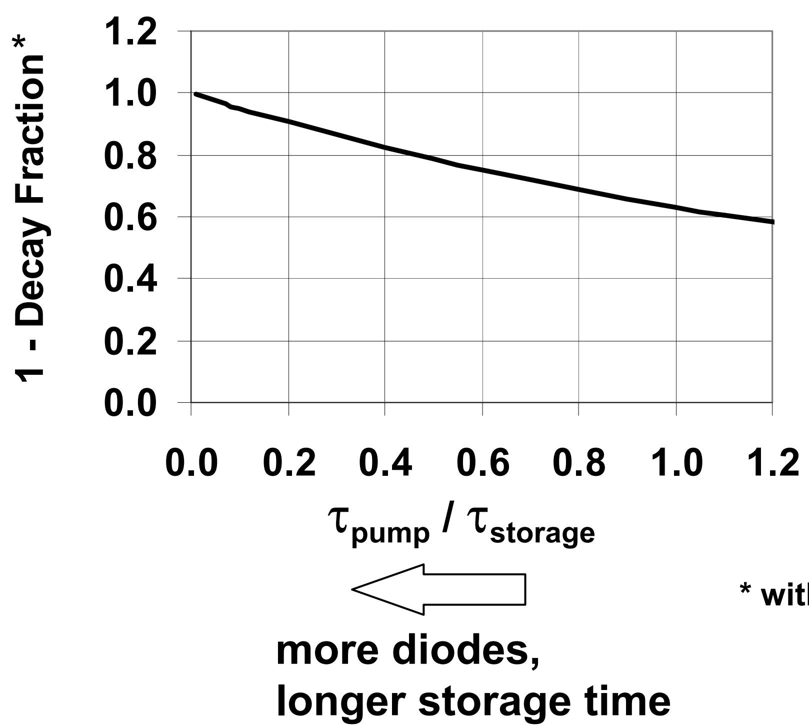
What if diodes remain expensive?

Using gain media with longer storage lifetime can reduce diode costs or improve efficiency

• Fluorescence decay during the pump pulse reduces efficiency



• Fluorescence decay is reduced by using
  - more diodes & shorter pump time, or
  - gain media with longer storage lifetime

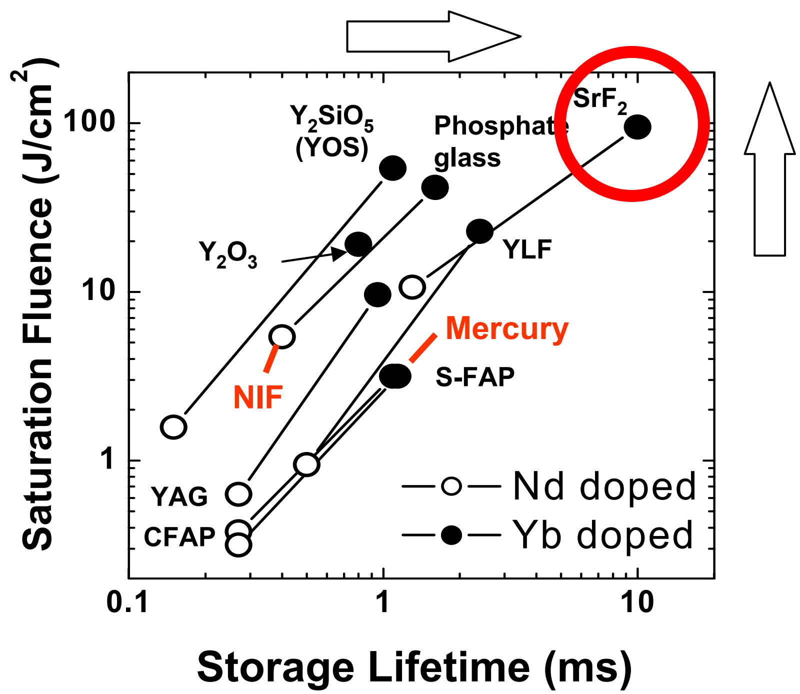


* without ASE

• At constant efficiency, # of diodes $\propto$ $1 / \tau_{storage}$

Gain media with long storage lifetimes tend to have high saturation fluences

Lower diode cost and/or higher storage efficiency – good !

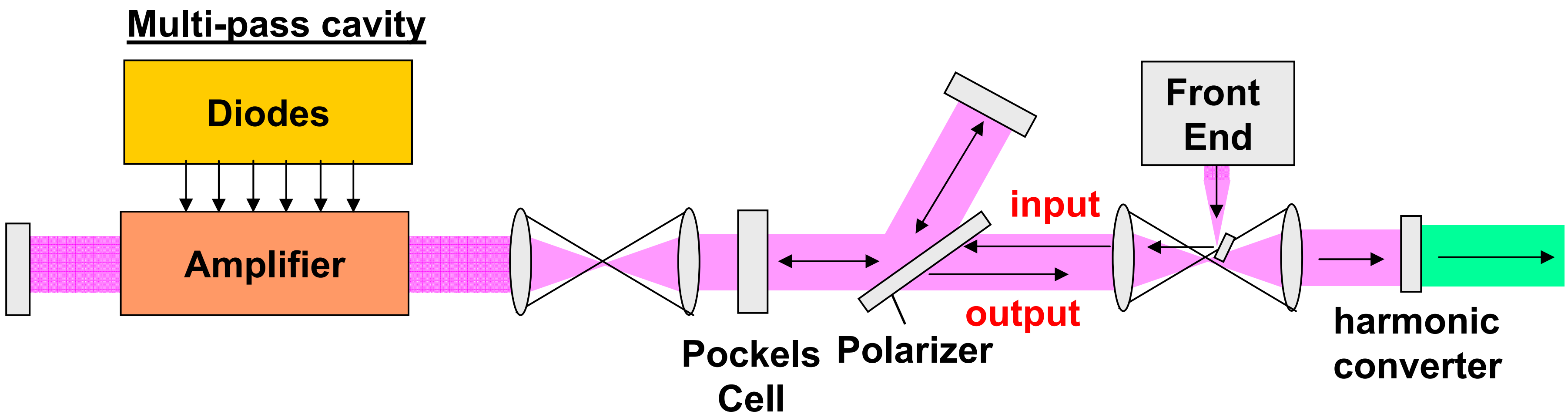


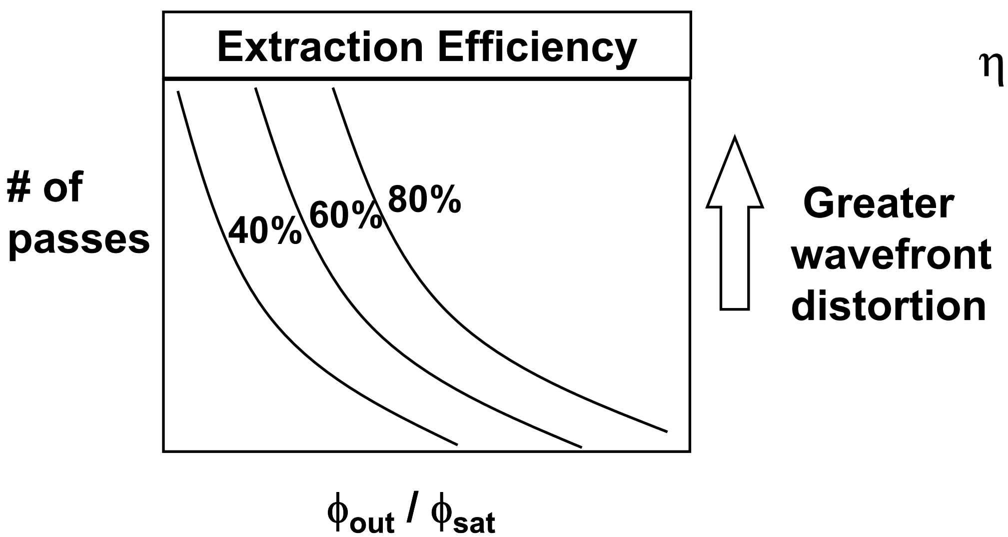
$\phi_{sat} \propto \tau_{storage}$

Higher stored energy density, fewer laser slabs needed, higher storage efficiency – good !

Harder to extract stored energy efficiently and safely – manageable

Stored energy can be safely extracted from gain media with high saturation fluence by passing the beam many times



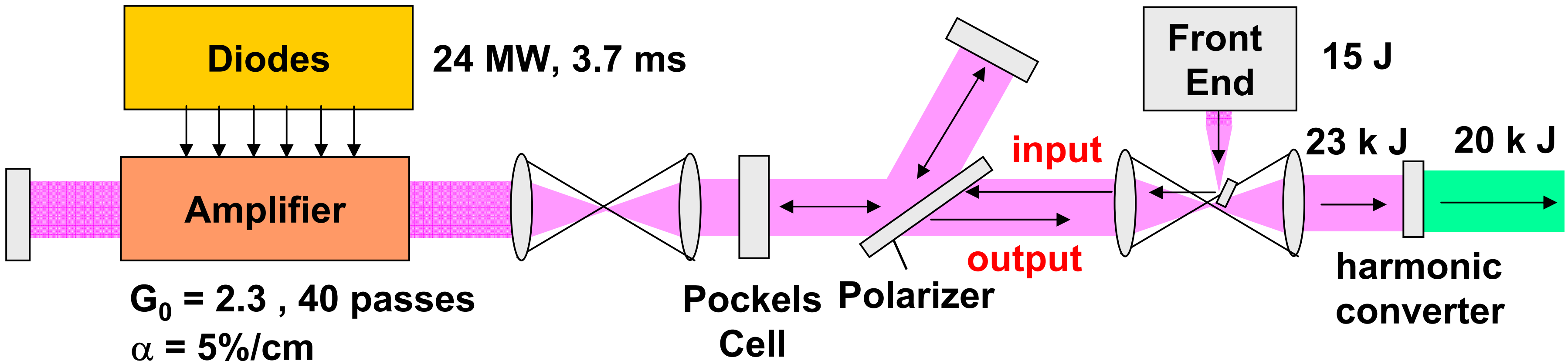


$$\eta_{extract} = \frac{\text{extracted beam energy}}{\text{stored energy}}$$

- Extraction efficiency depends on the cumulative fluence passed through the amplifier

A Yb:SrF_2 multipass design would be attractive even when diodes are expensive

Multi-pass cavity



G_0 = 2.3 , 40 passes
α = 5%/cm
ρ = 5.75 J/cm^3

ϕ_{sat} = 115 J/cm^2
$\tau_{storage}$ = 9.2 ms

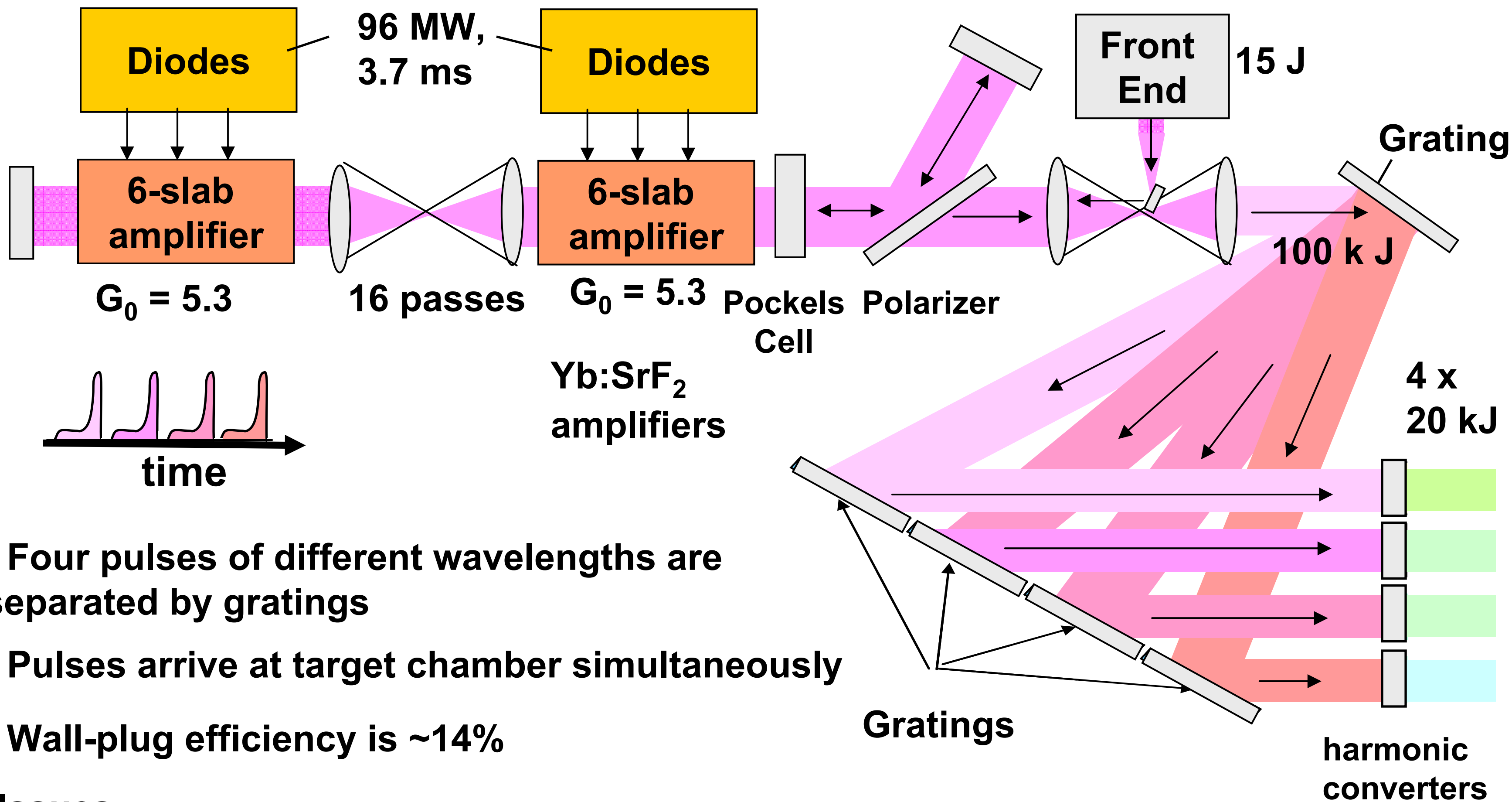
- 20 kJ / beamline requires high damage-threshold optics
- Overall wall-plug efficiency ~ 13%
- 100 beamlines are needed for a 2-MJ laser

Issues

- Extraction efficiency sensitive to passive losses
- Spatial-filter pinhole closure
- Heating of the Pockels Cell by absorbed light
- Wavefront distortion from many passes

	Diode costs	
Unit costs	@10¢ / W	@1¢ / W
20-kJ beamline	\$2.4 M	\$0.24 M
2-MJ system	\$240 M	\$24 M

Pulse-stacking methods can reduce beamline counts



- Four pulses of different wavelengths are separated by gratings
- Pulses arrive at target chamber simultaneously
- Wall-plug efficiency is ~14%

<u>Issues</u>

- High-damage-threshold gratings
- Gain bandwidth, reduced gain in wings

Only 25 beamlines are needed for a 2-MJ laser

Transparent ceramics are likely to revolutionize the manufacture of crystalline laser-gain media

- Strengths
  - –Crystalline material but can be made in large sizes, like glass
  - –Optical quality comparable to glass
  - –Rapid development path due to many users

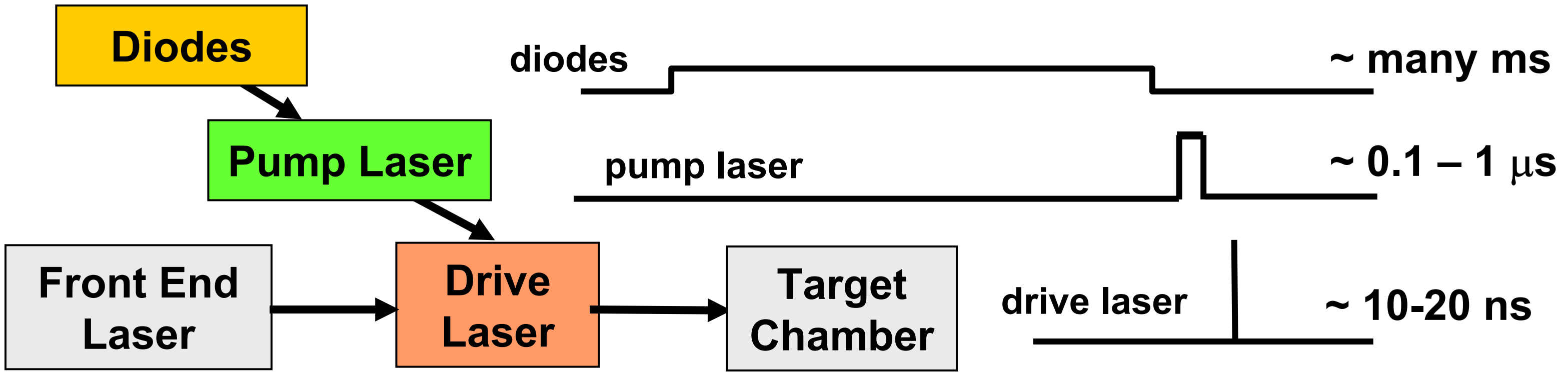
- Limitations
  - – High damage threshold under pulsed operation remains to be demonstrated
  - –Today only applicable to cubic structures – YAG, Y_2O_3, SrF_2

But what if

- damage thresholds stay low, or
- wavelength-division multiplexing doesn't work out

?

A possible solution is a laser-pumped laser

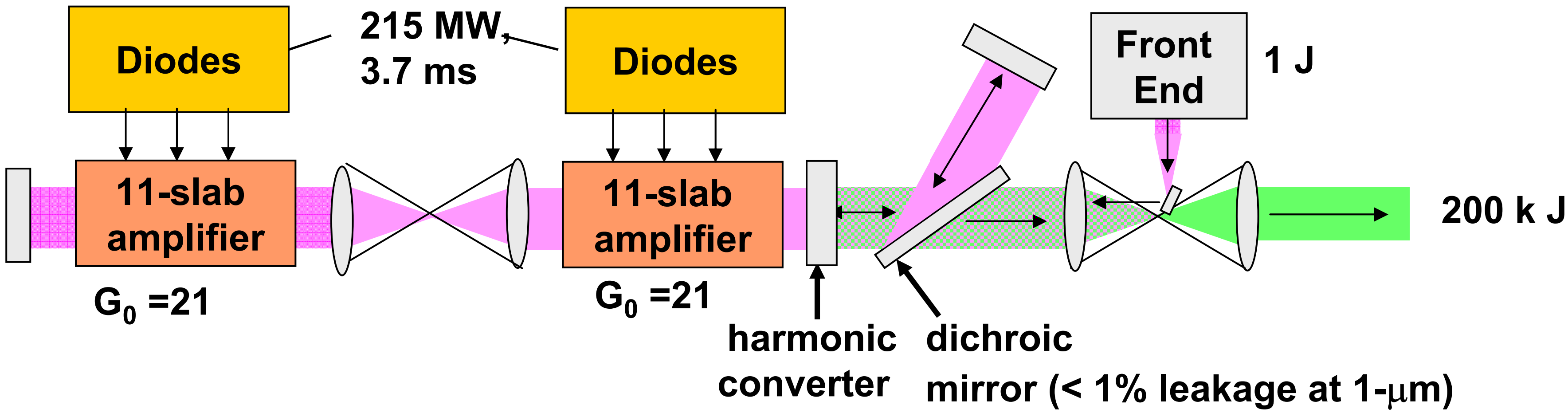


<u>Idea:</u>
Separate the two main amplifier functions so that each may be better optimized, separately:
- **storing energy**
- **producing 10-20-ns fusion pulses**

- **Optimize pump laser for storing energy**
  - use gain medium with a long storage lifetime, high saturation fluence
  - extracting at high fluence is OK when pulselengths are 100s of ns long

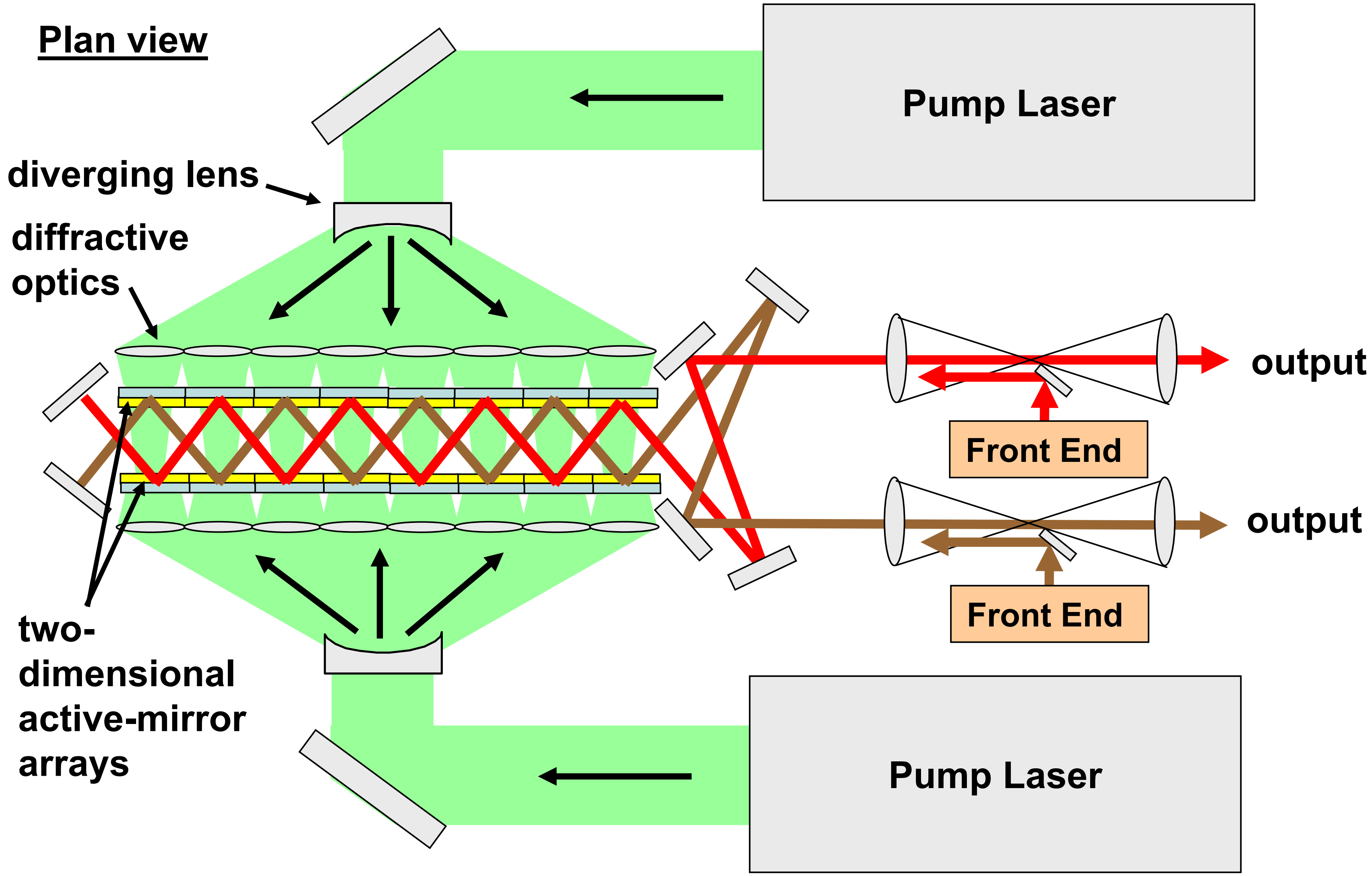
- **Optimize the drive laser for producing 10-20 ns-long pulses**
  - use gain medium with low saturation fluence, short storage lifetime
  - short storage lifetime is OK since energy is extracted quickly after pumping (< 1μs later)

A pump-laser design using Yb:SrF_2 produces 200 kJ per beamline at 0.5μm

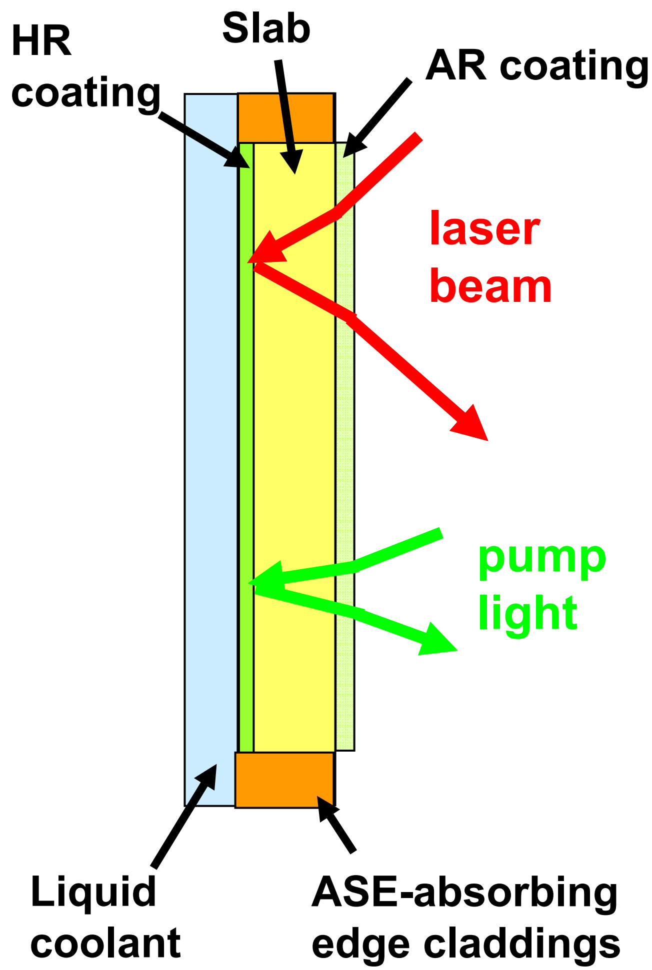


- Damage fluences >200 J/cm^2 are projected for pulselengths of ~100 ns
  - damage fluence scales as ~ $\tau^{1/2}$
- Harmonic conversion necessary for pumping some lasers, such as titanium-doped sapphire
- Intracavity doubling can be highly efficient
- The harmonic converter would require significant development
- Only ~15-20 beamlines are needed to pump the driver beam lines of a 2-MJ fusion laser

Pump light could be delivered through the sides of the active-mirror arrays



Active mirrors amplify laser pulses that make two passes through the laser slab



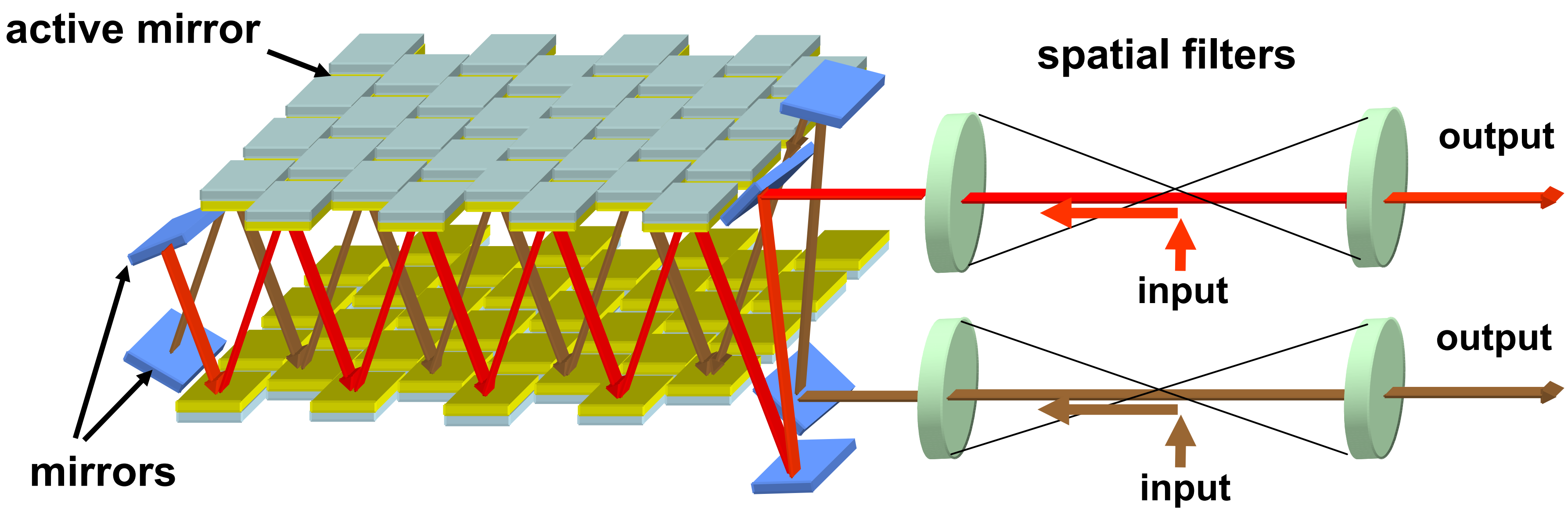
- The main laser beam is transmitted through a front-surface AR coating and is reflected by a rear-surface mirror
  - -operation is inherently double-pass

- Liquid cooling has advantages relative to gas cooling
  - less costly hardware
  - lower power consumption

- We are studying ways for controlling parasitic laser oscillations
  - coolants that absorb amplified spontaneous emission (ASE)

- Key issue is thermal gradients causing wavefront distortion
  - titanium-doped sapphire has high thermal conductivity and would have relatively low thermal distortion

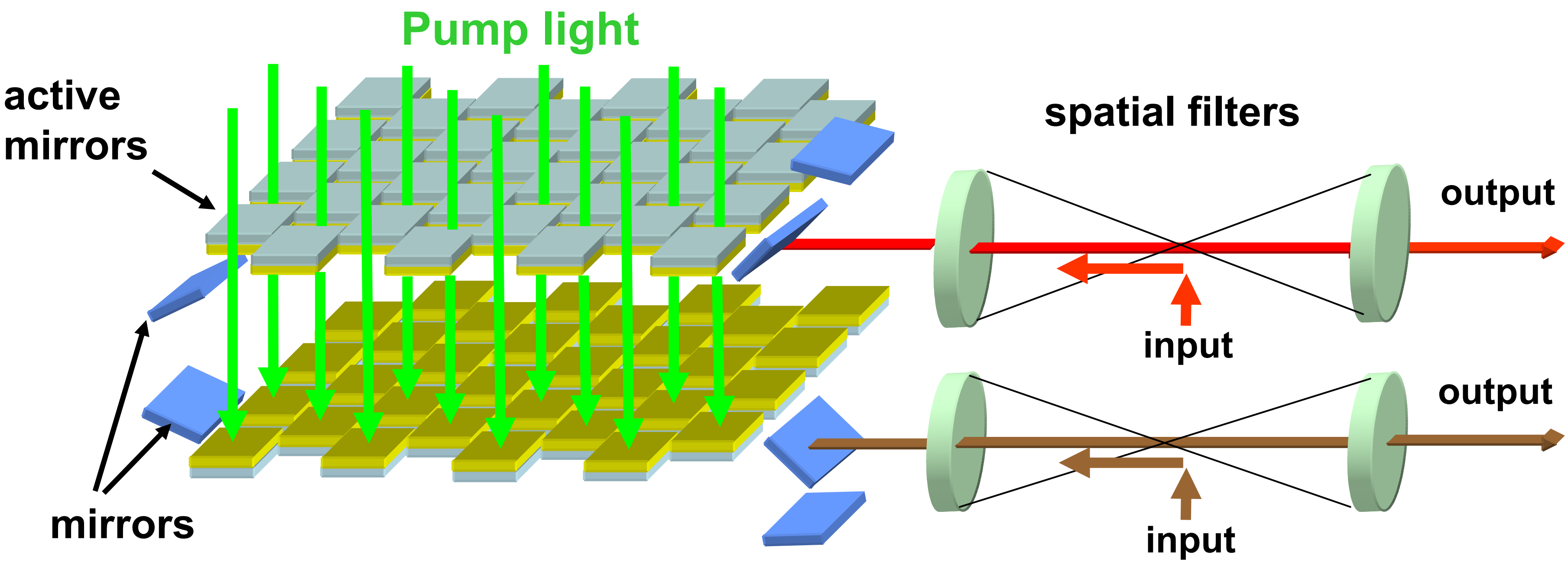
Amplifier cavities can be set up around the active-mirror arrays by using mirrors and spatial filters



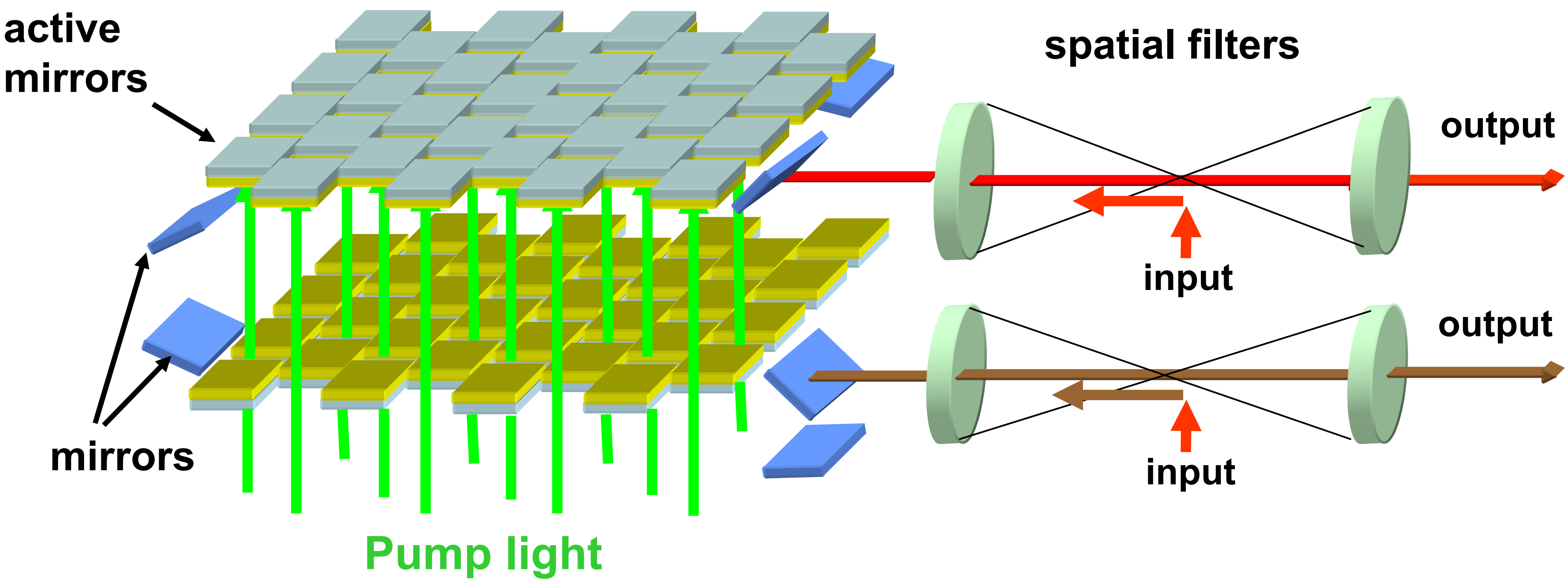
- Only one pair of beamlines are shown here, for clarity

- Not shown are:
  - beam lines that are parallel to the illustrated beamlines
  - beam lines that are orthogonal to the illustrated beamlines

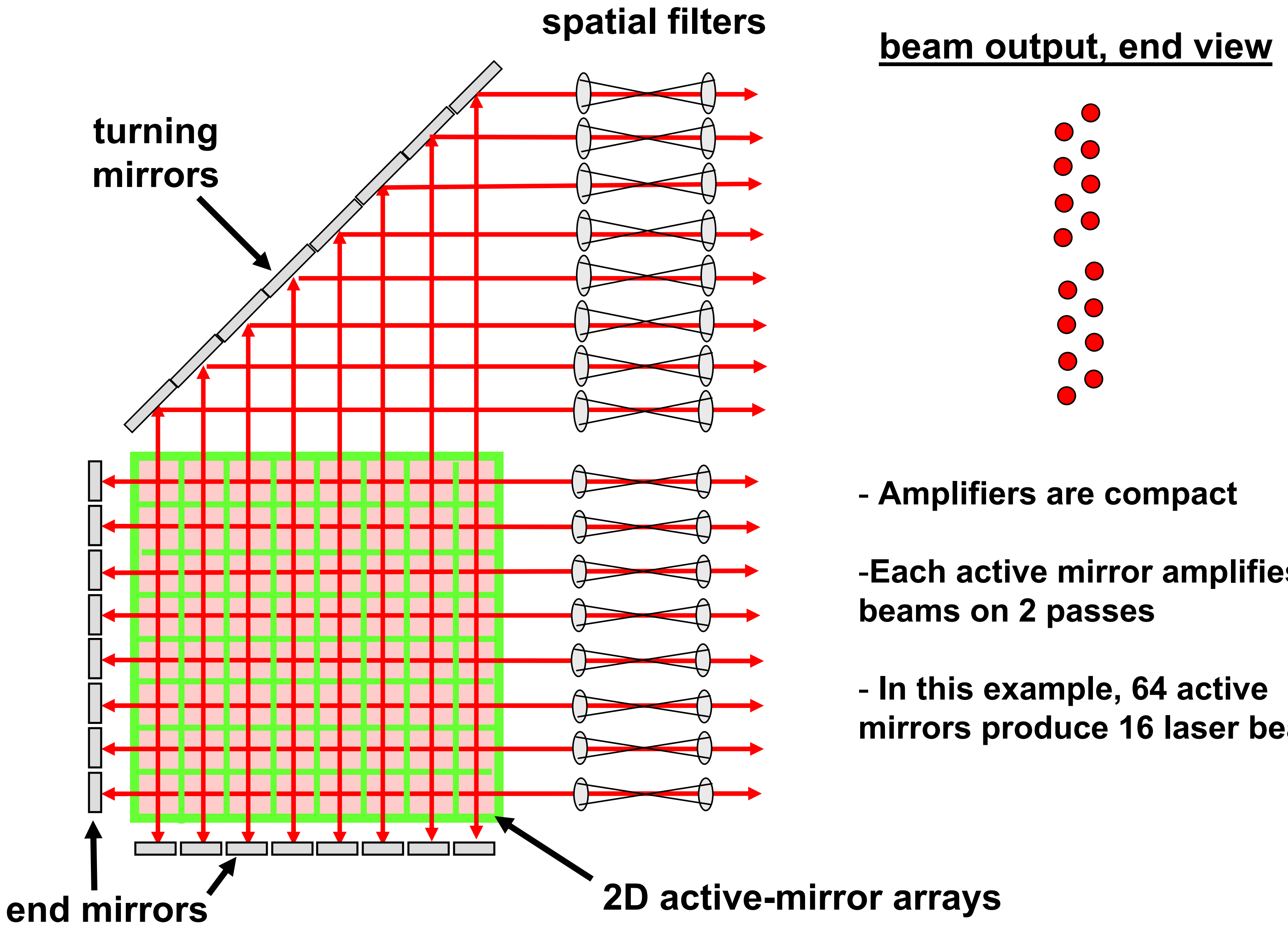
Pump light for each array is delivered through openings in the facing array



Pump light for each array is delivered through openings in the facing array



A top view shows how beamlines enter and exit the array



- Amplifiers are compact

-Each active mirror amplifies 2 beams on 2 passes

- In this example, 64 active mirrors produce 16 laser beams

Significant increases in laser efficiency appear to be possible

Eff. (%)	NIF	Future DPSSL
Power Conditioning	82	87 - 93
Diodes / Lamps	50	70 - 90
Pump transport	60	91 - 99
Absorption	40	91 - 99
Quant Defect	60	83 - 93
1 – Decay Fraction	45	58 - 82
Extraction & Fill	51	60 - 90
Beam transport	93	93 - 99
Freq Conv	60	85 - 95
Cooling	NA	83 - 93
Total (%)	0.75	15 - 30

- There are tradeoffs between capital costs and efficiency
- It is our job to study tradeoffs for practical systems

Studies are underway at LLNL to develop low cost, high-efficiency laser drivers

PHOTON SCIENCE & APPLICATIONS

- Our work builds upon experience with large flashlamp-pumped laser systems and smaller diode-pumped systems
  - NIF, Mercury and SSHCL

- We have concentrated first on opening up the design space
  - application of developing technologies
  - blue-sky ideas

- Significant reductions in costs and increases in efficiency appear feasible
  - only tens of beamlines
  - > 20% efficiency

- We plan to undertake more detailed performance calculations and design development in coming months

A Laser-based Fusion Test Facility (FTF)

Presented by: Steve Obenschain

Plasma Physics Division
U.S. Naval Research Laboratory

IFE Science and Technology Strategic Planning Workshop
San Ramon, California
April 24 - 27, 2007

FTF philosophy

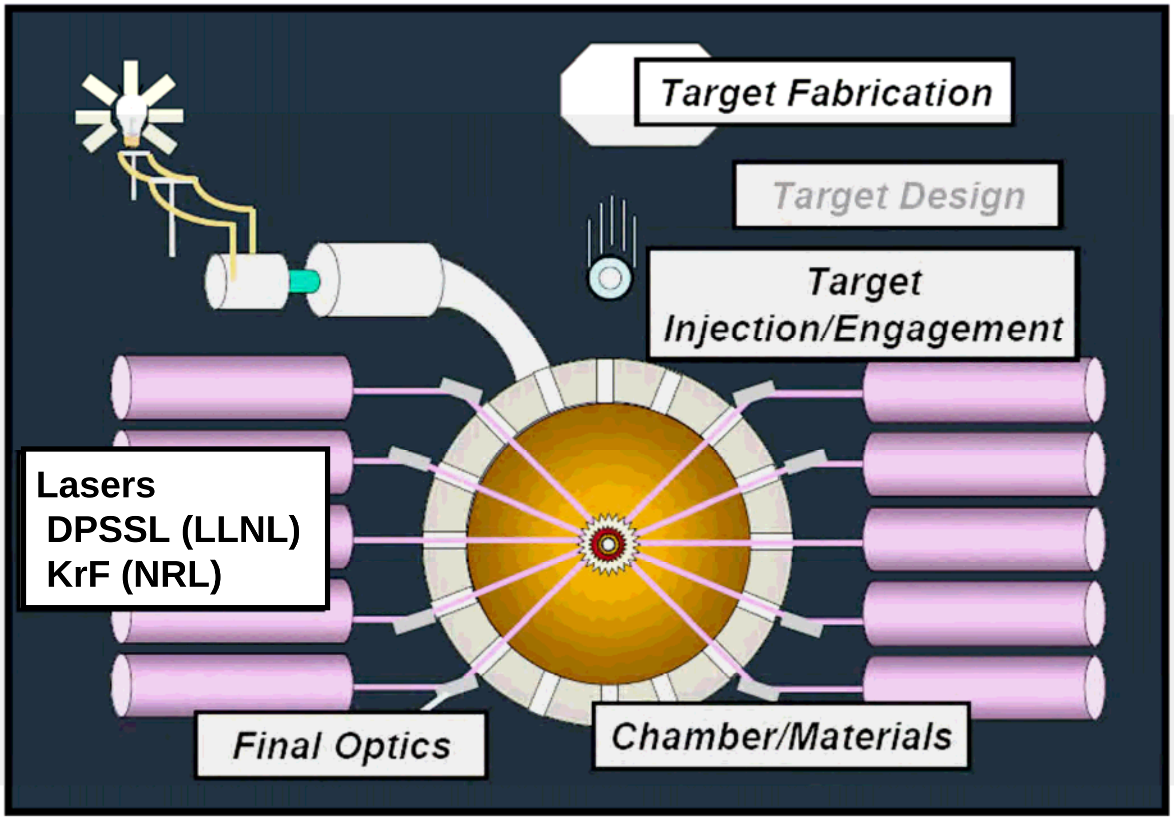
- **Next large ICF/IFE facility should be much closer to reactor parameters. (e.g. routine ignition, high rep rate, high duty cycle)**
- Yet it has to be a research device. (IFE S&T, develop operating procedures)
- Reducing cost and time for implementation are very important.
- The vision must inspire the current paying customer and interest future customers (energy industry).to get required resources
- Effort must be compatible with and foster advances/inventions.
- **Timely success of a particular IFE approach should create resources for others.**

We have identified and are developing a path to accelerate the deployment of fusion energy with the FTF as a centerpiece

- **Based on inertial fusion energy (IFE) using lasers**
  - Scientific basis: US and international ICF programs
  - Technical basis: US HAPL program

- **We believe the low risk, fastest path to fusion:**
  - Develop S&T for key components in concert
  - Guided by goal of an attractive power plant

The HAPL Program:
Developing the science & technologies needed for laser fusion energy



HAPL= High Average Power Laser program administered by NNSA

High-Average-Power-Laser (HAPL) Program: develops S&T for inertial fusion energy via directly-driven targets with lasers

HAPL meeting #14, Oak Ridge National Lab, March 2006

Government Labs

1. NRL
2. LLNL
3. SNL
4. LANL
5. ORNL
6. PPPL
7. INEL
8. SRNL/SRS

Universities

1. UC San Diego
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. UC Santa Barbara
7. UC Berkeley
8. U North Carolina
9. Penn State Electro-optics

Private Industry

1. General Atomics
2. L-3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. Optiswitch Technology
14. Research Scientific Inst

The U.S. HAPL program is developing two lasers:

- ♦ **Diode Pumped Solid State Laser (DPPSL)**
- ♦ **Electron beam pumped Krypton Fluoride Laser (KrF)**

Both lasers are on track to attain their initial performance goals

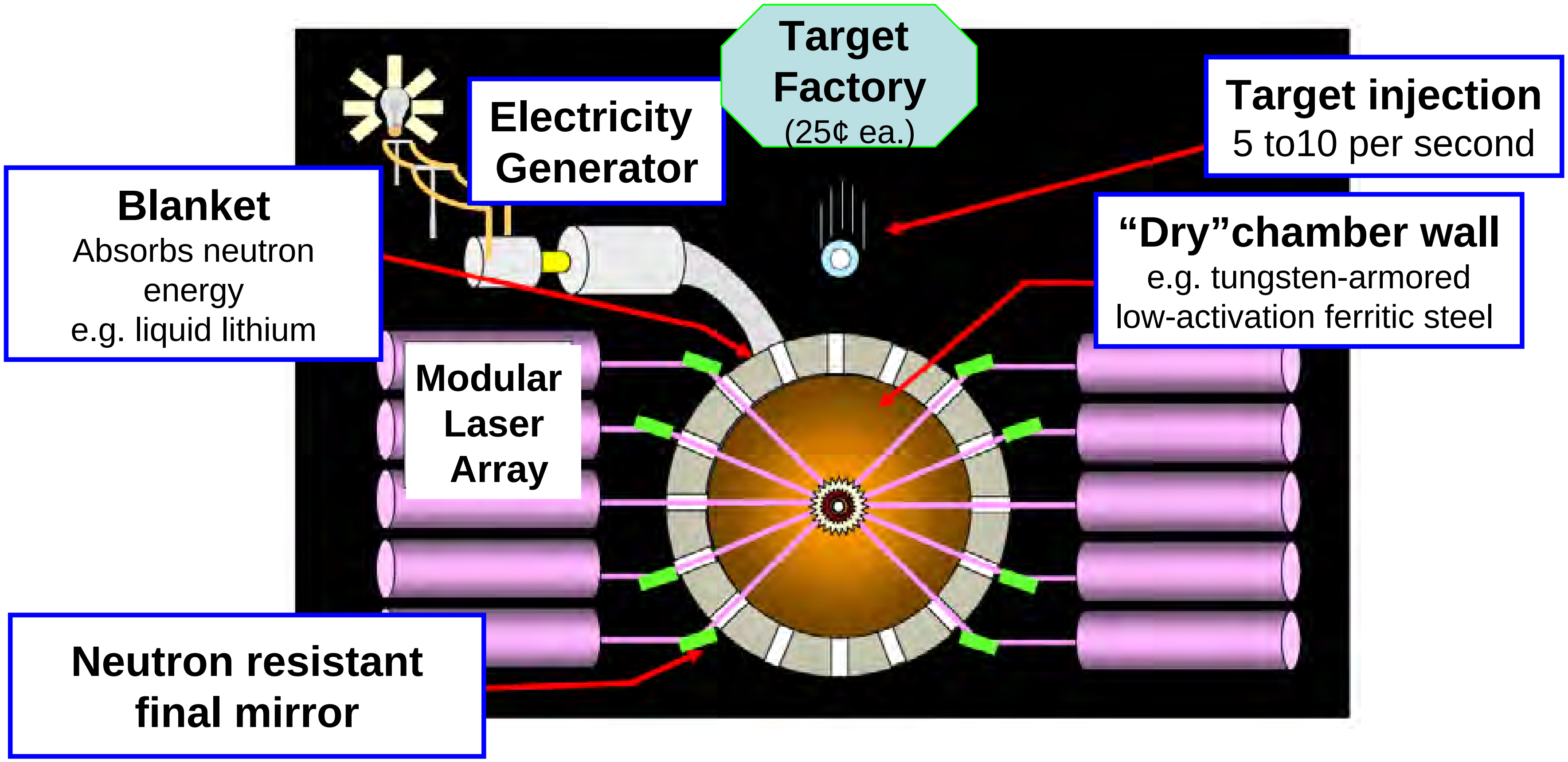
Mercury DPSSL Laser (LLNL)

- Goal of 100 J @ 1051 nm
- 10 Hz
- 2ω (525 nm) and 3ω (350 nm) options
- Potential for efficiencies >10%
- Benefits from large single-shot solid state laser technologies.

Electra KrF Laser (NRL)

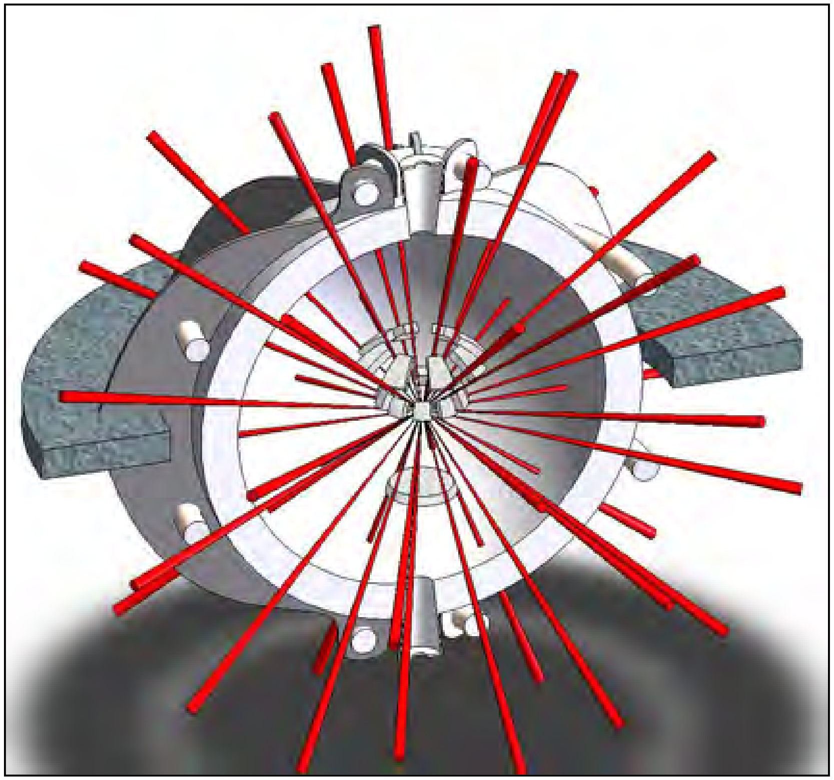
- Goal of 700 J @ 248 nm
- 5 Hz
- Predict 7% wall plug efficiency for IFE
- Probably lower cost option re Joules/$
- Best direct-drive option re target physics

Typical GW (electrical) direct-drive designs have ~**3 MJ** laser drivers @ 5-10 Hz



Can we construct a facility that provides the information needed to design a power plant with a substantially smaller laser driver?

500 kJ (<1/3rd the design 3ω energy of NIF) is predicted to be sufficient for direct drive ignition and **gains >50×** with a KrF driver



Fusion Test Facility (FTF)

- **Direct laser drive**
- **Sub-megaJoule laser energy**
- **High-Rep operation (5Hz)**
- **Goal of ~150 MW fusion power**
- **High flux neutron source**
- **Lies on a development path to a power plant**

Development Plan for Laser Fusion Energy

Stage I
2008-2014

Develop full-size components
- 25 kJ 5 Hz laser beam line
- (first step is 1-2 kJ laser beam line)
- Target fabrication & injection
- Power plant & FTF design

Target physics validation
- Calibrated 3D simulations
- Hydro and LPI experiments
- Nike, NexStar, OMEGA, NIF

Stage II
2015-2023
operating ~2019

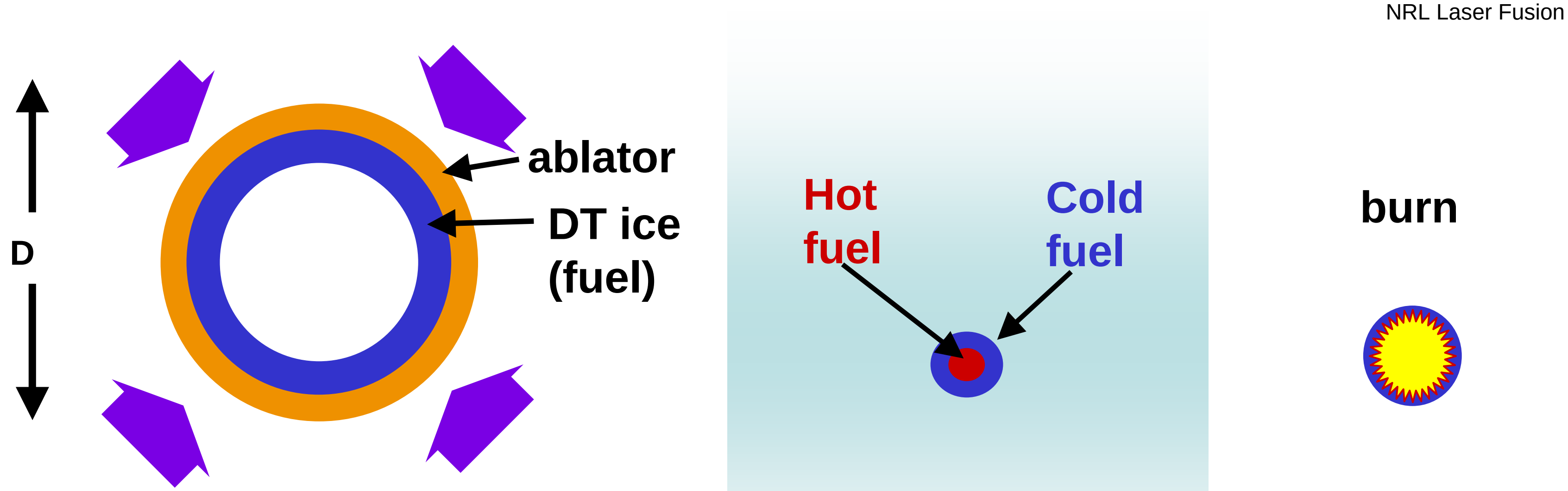
Fusion Test Facility (FTF or PulseStar)
- 0.5 MJ las er-driven implosions @ 5 Hz
- Pellet gains ~60
- ~150 MW of fusion thermal power
- Target physics
- Develop chamber materials & components.
- **Continue offline S&T development**

Stage III
2024-2032

Prototype Power Plants (PowerStars)
- Power generation
- Operating experience
- Establish technical and economic viability

How to reduce substantially laser energy with direct laser drive

NRL Laser Fusion



Pellet shell imploded by laser ablation to v ≅ 300 km/sec for >MJ designs

- Reduce pellet mass while increasing implosion velocity (to ≥400 km/sec)
- Increase peak drive irradiance and concomitant ablation pressure (~2x)
- Use advanced pellet designs that are resistant to hydro-instability
- Use deep UV light and large $\Delta\omega$

Deep UV laser should allow increased ablation pressure and robust pellet designs at reduced energy

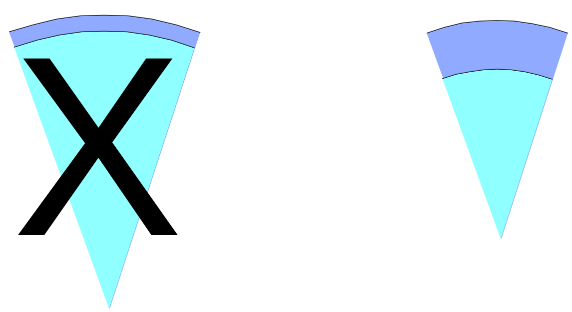
Laser plasma instability limits peak $I\lambda^2$

P scales approximately as $I^{7/9}\lambda^{-2/9}$

$\rightarrow$ **P_{MAX} scales as $\lambda^{-16/9}$**

Factor of $(351/248)^{-16/9}$ = 1.85 advantage for KrF's deeper UV over frequency-tripled Nd-glass

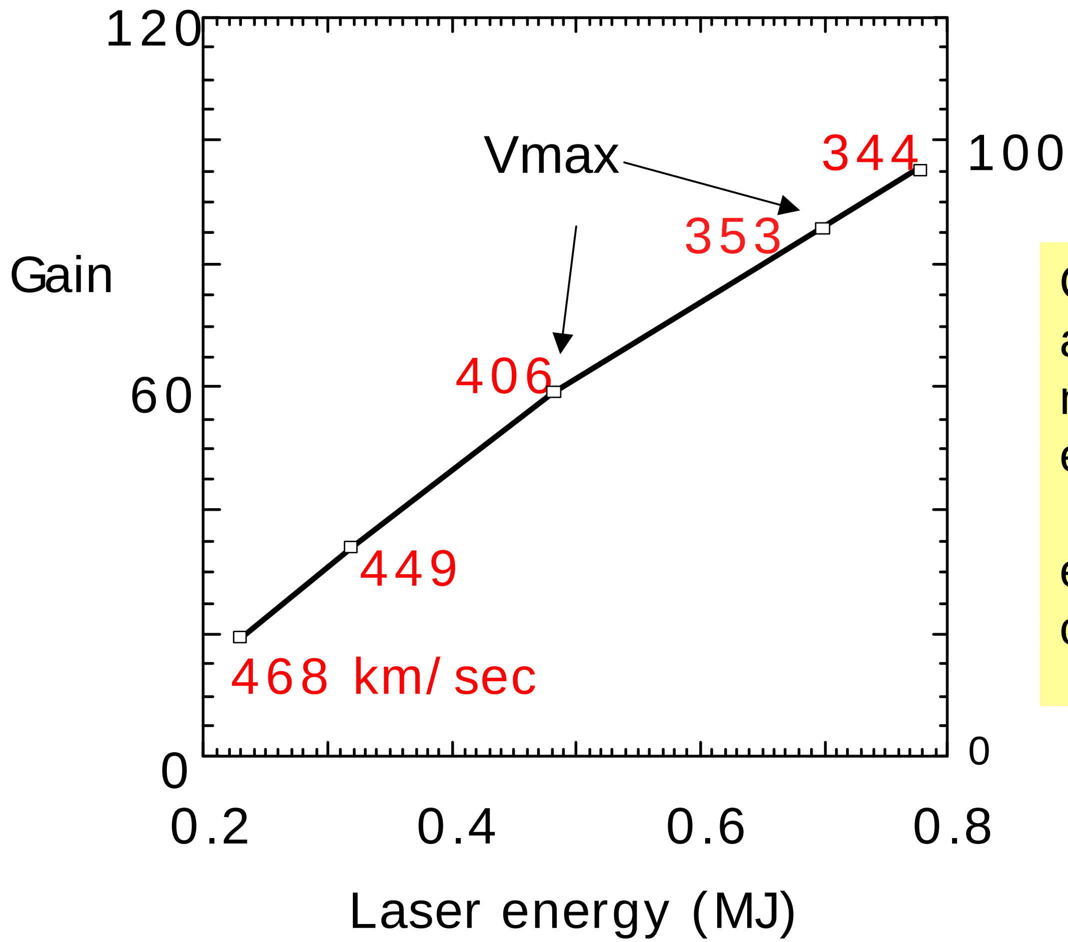
High ablation pressure (>200 MB) allows the higher implosion velocity with low aspect ratio targets that are more resistant to hydrodynamic instability



Gain increases and optimum implosion velocity decreases with laser energy

NRL Laser Fusion

1-D gains with conventional (no spike) pulse shape



KrF LASER
~$2.5x10^{15}$ W/cm^2 Imax

Other compatible approaches such as shock and impact "fast ignition" may allow higher gains at these energies.

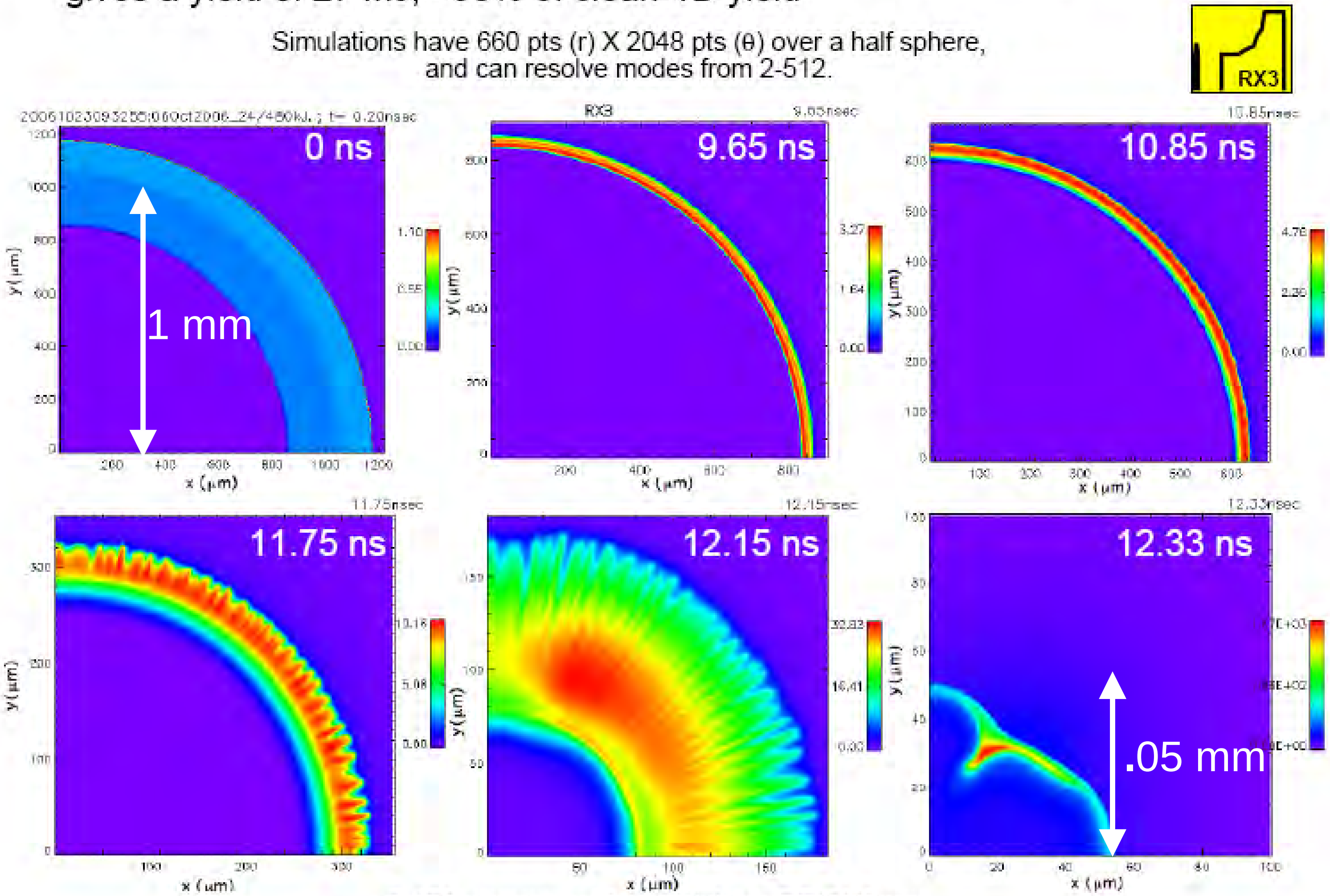
e.g.John Perkins & R. Betti this conference

Multimode high-res 2D simulation with 480 kJ KrF Gain of 56× despite pellet surface imperfections

NRL Laser Fusion

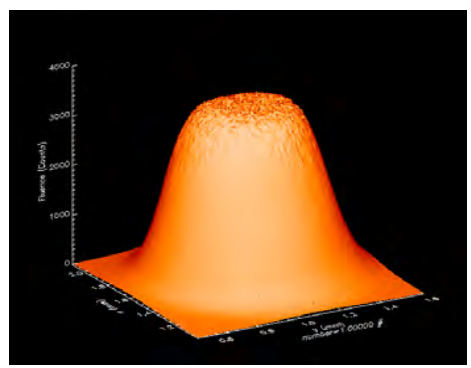
Result: With NIF-spec.-equivalent outer surface finish, the RX3 pulse gives a yield of 27 MJ, ~90% of clean-1D yield

Simulations have 660 pts (r) X 2048 pts (θ) over a half sphere, and can resolve modes from 2-512.



0.478 μm rms surface finish on DT/CHfoam

Krypton-fluoride laser facilities at NRL

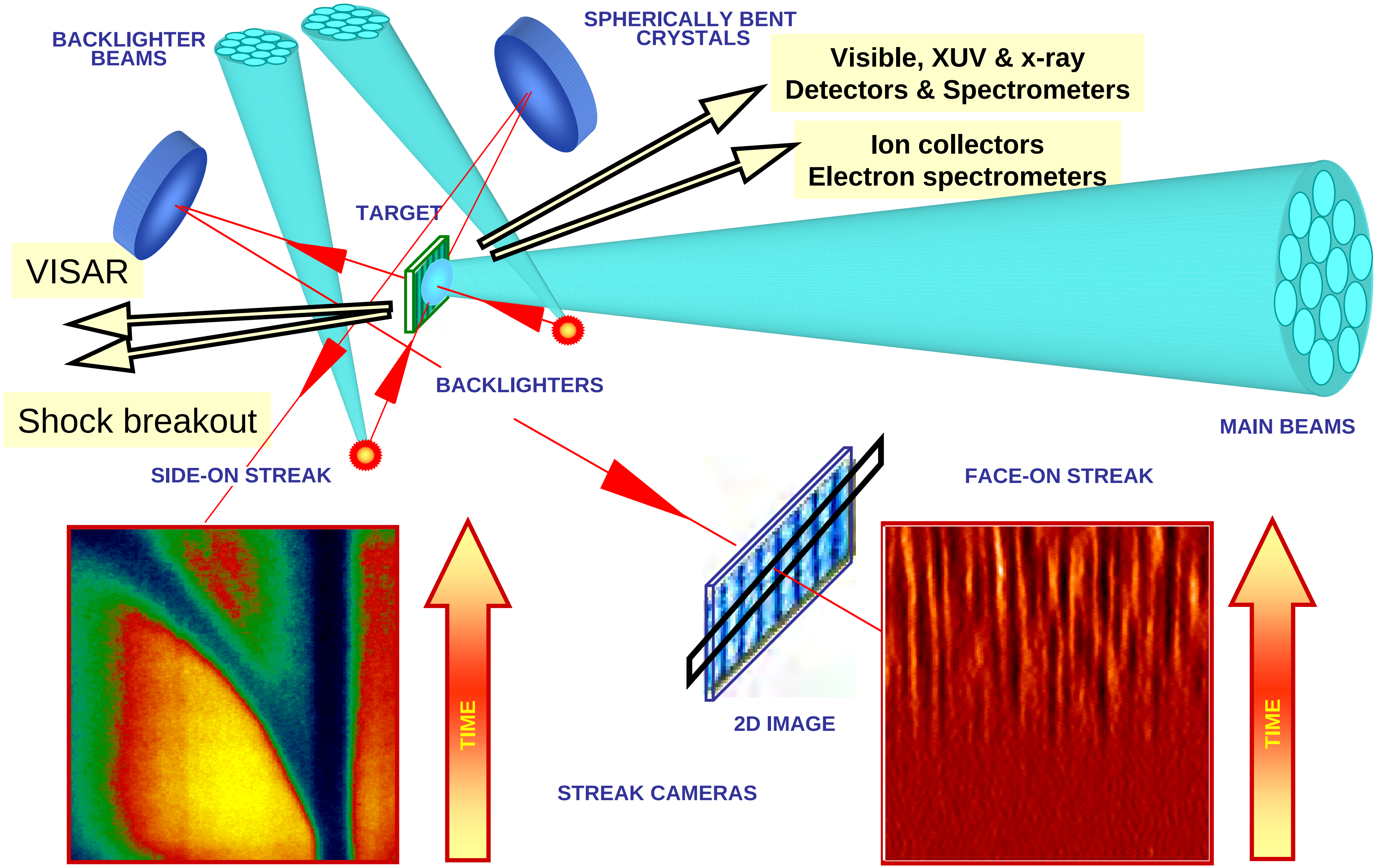


Nike laser provides highly uniform target illumination (best by far in the business)

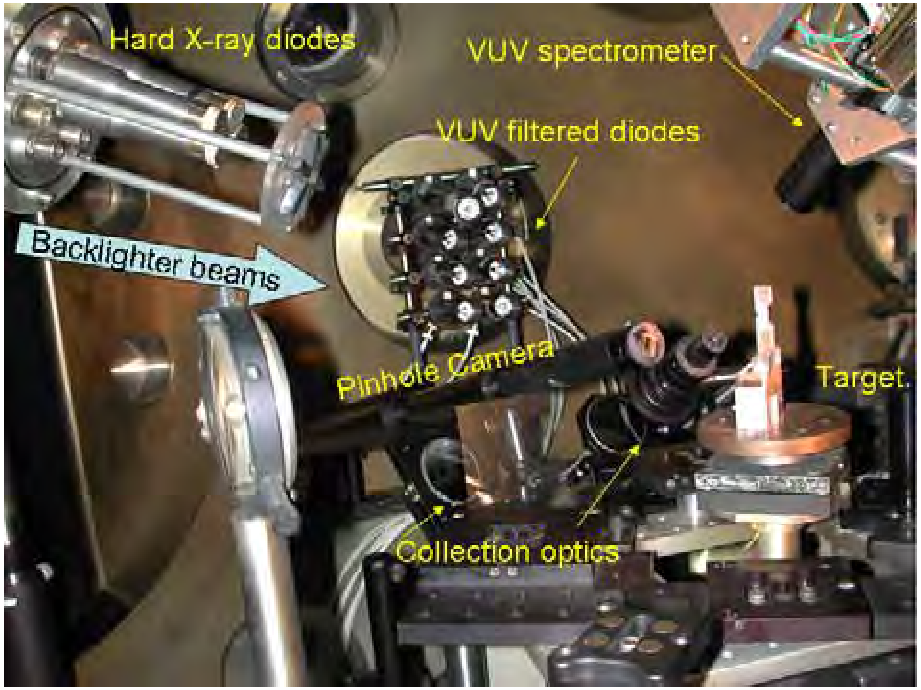
&

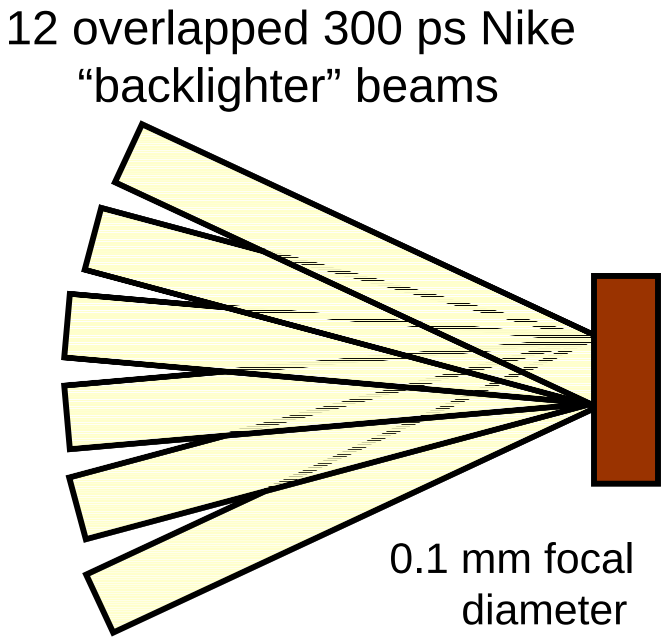
deepest UV

Nike is used to study laser-accelerated planar targets



Initial Nike laser plasma experiments show no evidence for parametric instability @ 2-3x10^{15} W/cm^2





- So far no hard x-rays, no Raman scatter, no 3/2 omega
- Studies will be extended to 10^{16} W/cm^2 at 1-2kJ on Nike
- Need more energy to simulate FTF-scale plasma (e.g. with proposed 25 kJ "NexStar" KrF facility, also OMEGA EP and NIF)
- Laser plasma instability will limit max usable intensity and determine the minimum FTF driver energy.

Electra high-rep rate KrF laser systems

Development is guided by simulation codes

main amp 30 cm x 30 cm aperture

pre-amp 10 cm x 10 cm

300-700 J @ 248 nm
120 nsec pulse
1 - 5 Hz
25 k shots continuous at 2.5 Hz (single sided)

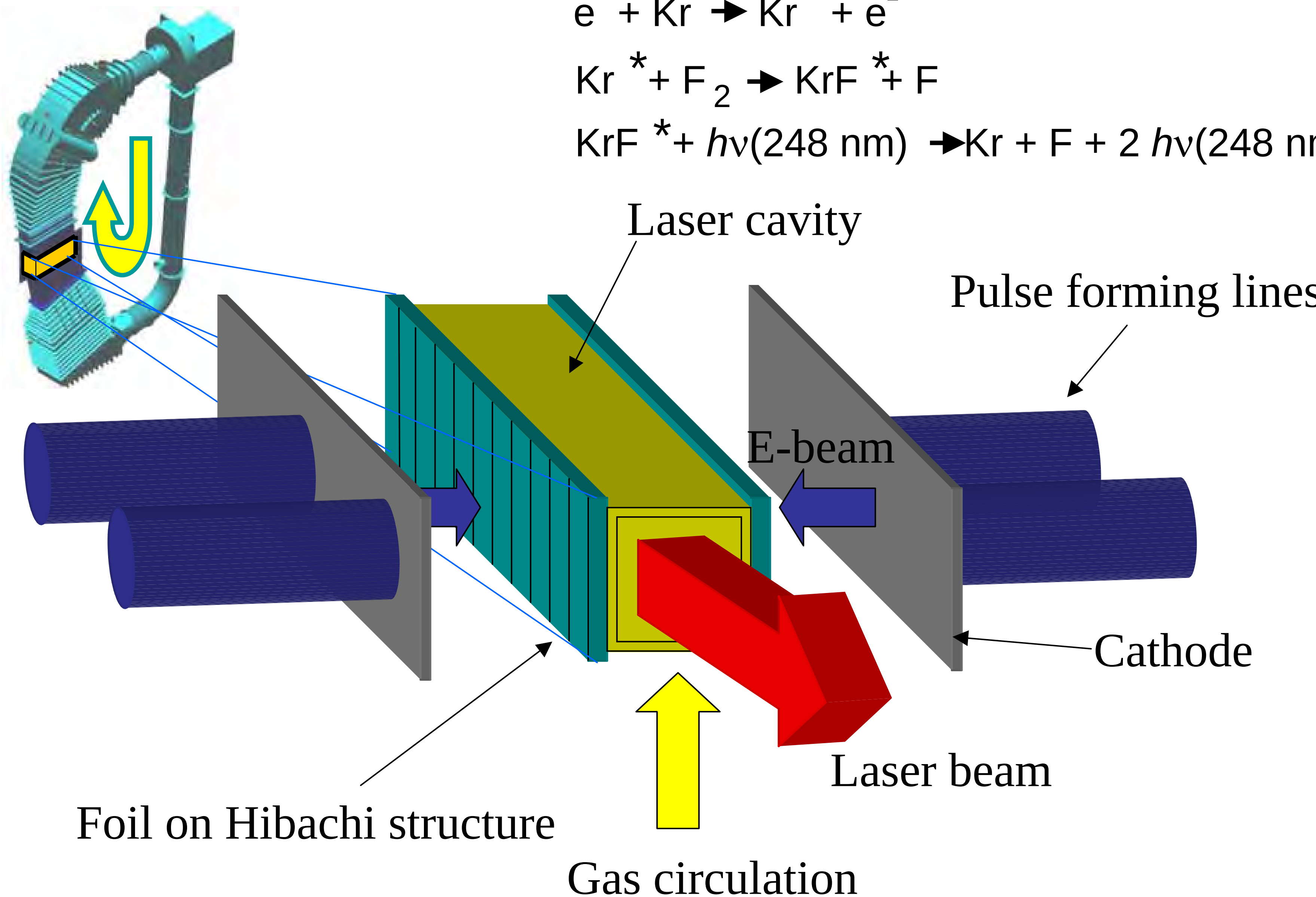
Pre-amp is upgradeable to all-solid-state HV switching

Components of E-beam pumped KrF laser

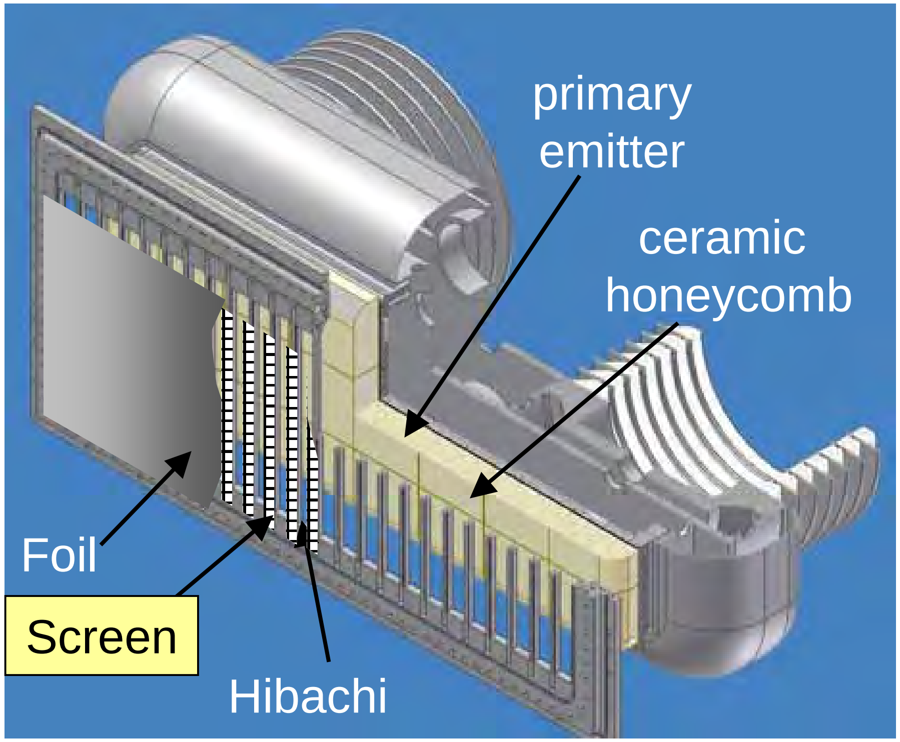
$$e^- + Kr \rightarrow Kr^* + e^-$$

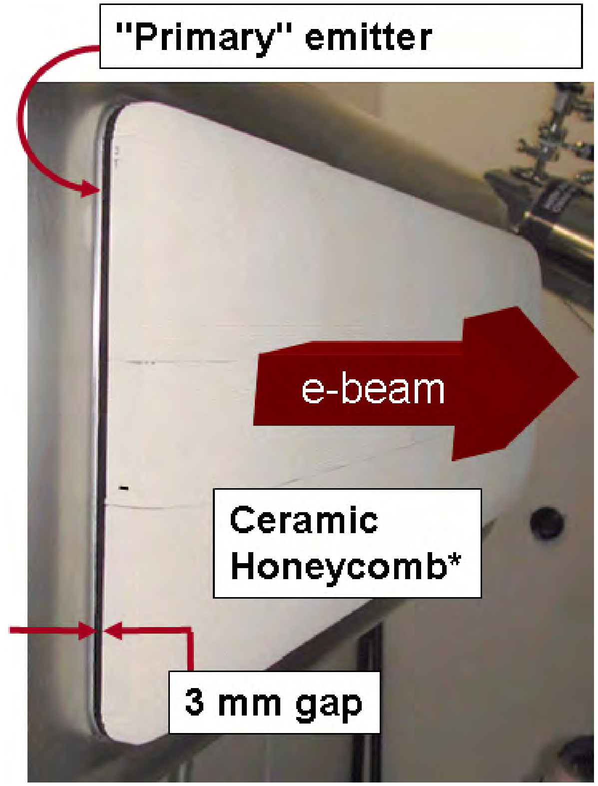
$$Kr^* + F_2 \rightarrow KrF^* + F$$

$$KrF^* + h\nu(248\ \text{nm}) \rightarrow Kr + F + 2\,h\nu(248\ \text{nm})$$



Ceramic Cold Cathode allows long duration laser runs with Electra 30-cm aperture amplifier





Ceramic Cathode was installed on the larger Nike 60-cm amplifier and found to also suppress a deleterious electron beam instability that heated the beam and thereby limited the efficiency in large diodes.

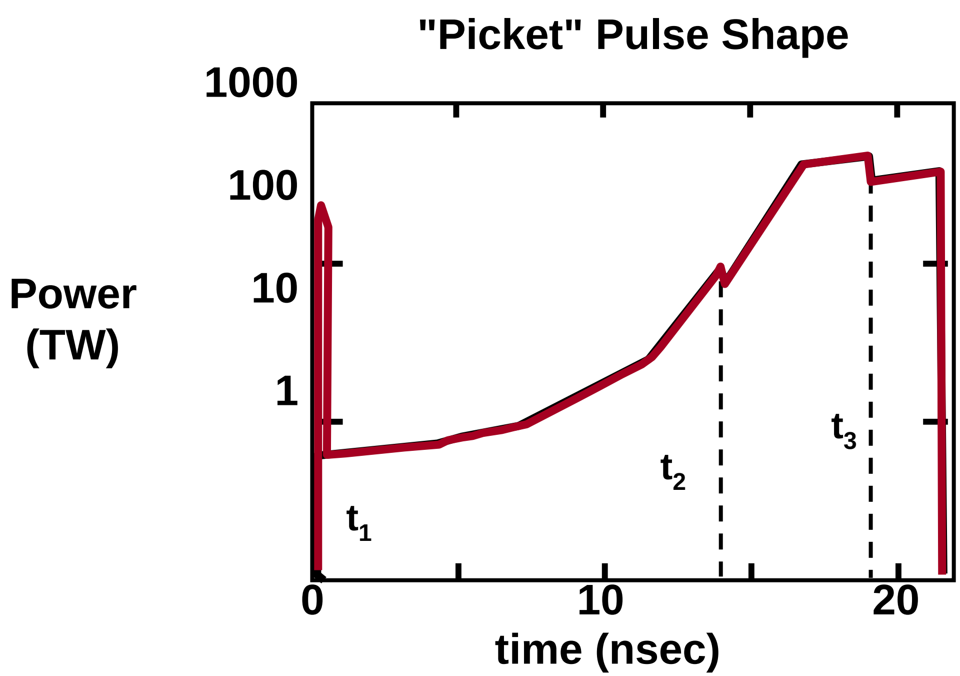
Based on our research an IFE sized KrF system is projected to have a wall plug efficiency ~7%.

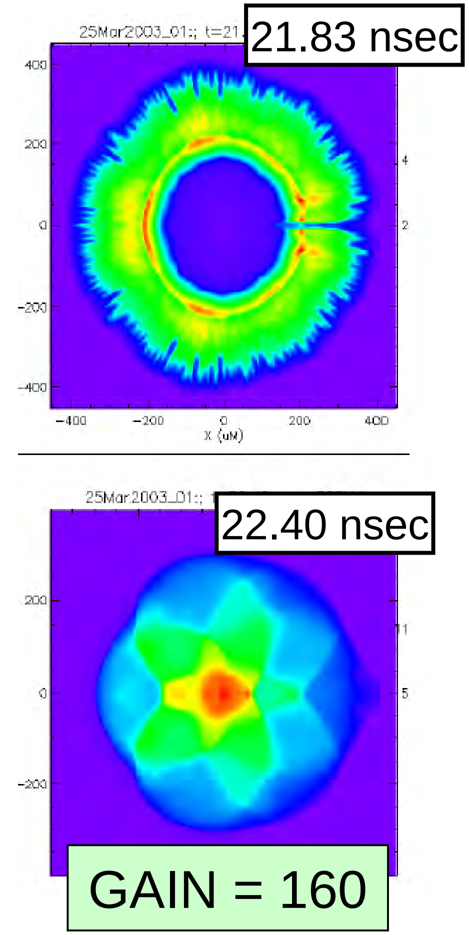
KrF	**Based on Electra expt's**	**12%**
Pulsed Power	***Advanced Switch***	***85%***
Hibachi Structure	***No Anode, Pattern Beam***	***80%***
Optical train to target	**Estimate**	**95%**
Ancillaries	**Pumps, recirculator**	**95%**
Global efficiency		**7.4%**

NRL 2-D computer simulations predict target *gains ~ 160* with 2.5 MJ KrF laser driver

laser-efficiency x gain > 10

Laser = 2.5 MJ





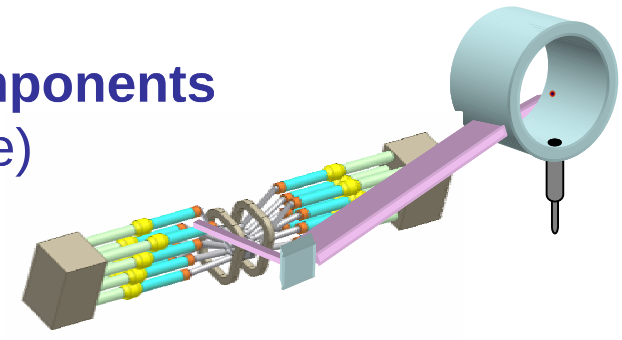
Similar predictions made by:
University of Rochester
Lawrence Livermore National Laboratory

Our three-stage plan for laser IFE:

Key elements are developed and implemented in progressively more capable IFE oriented facilities

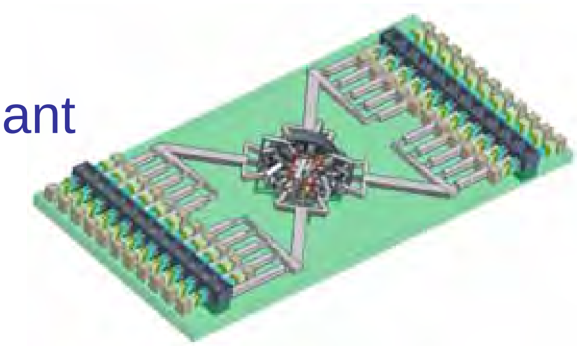
<u>Stage I</u> (~6 years) : Develop full size components

Laser module (25 kJ 5 Hz KrF beamline)
Target fabrication/injection/tracking
Chamber
Verify pellet physics



<u>Stage II</u> (~2014-2022): Fusion Test Facility (FTF)

Demonstrate physics / technologies for a power plant
Operating: ~2019

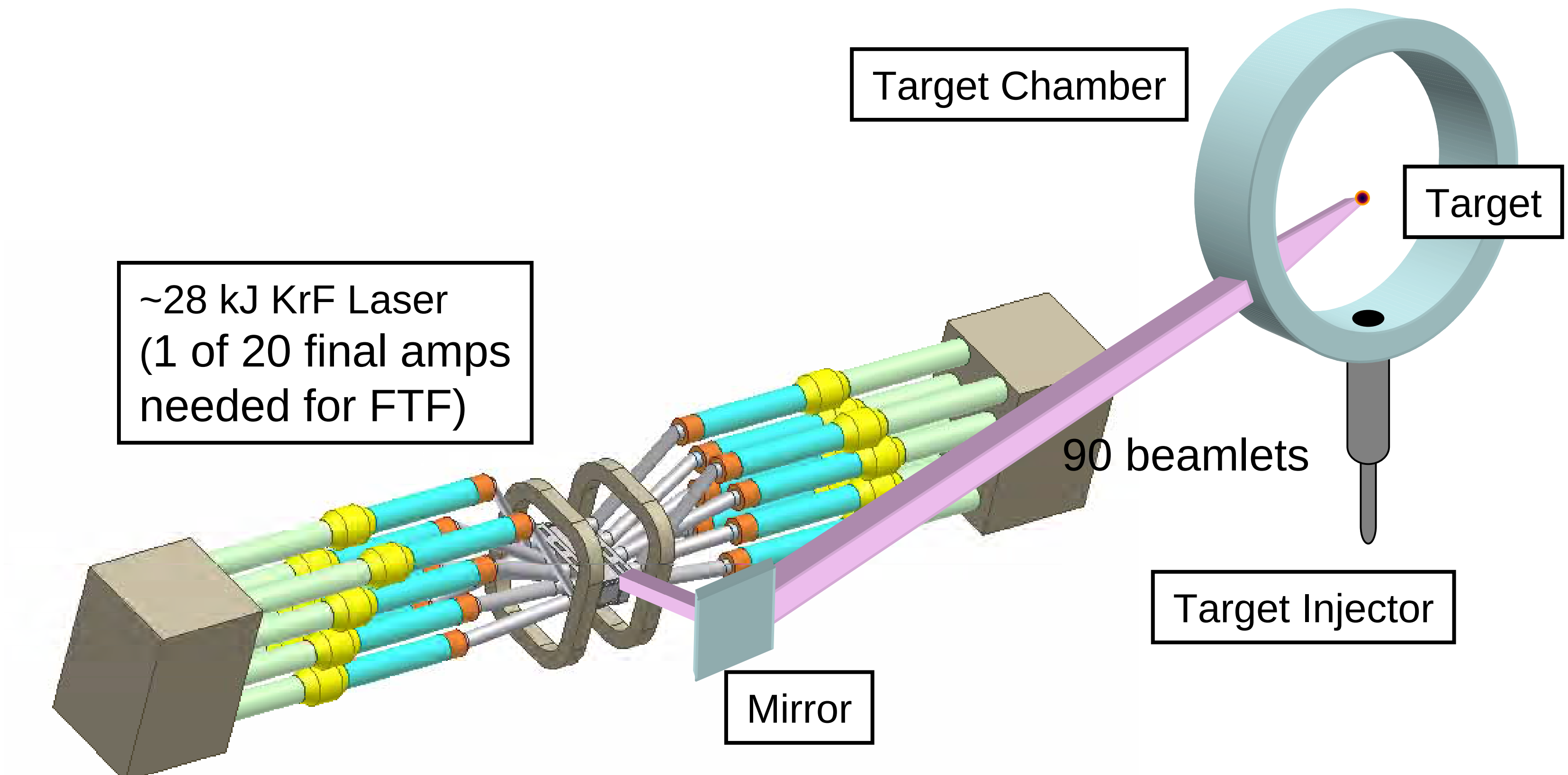


<u>Stage III</u> (~2024 - 2032): Prototype Power plant(s)

Electricity to the grid
Significant participation by private industry

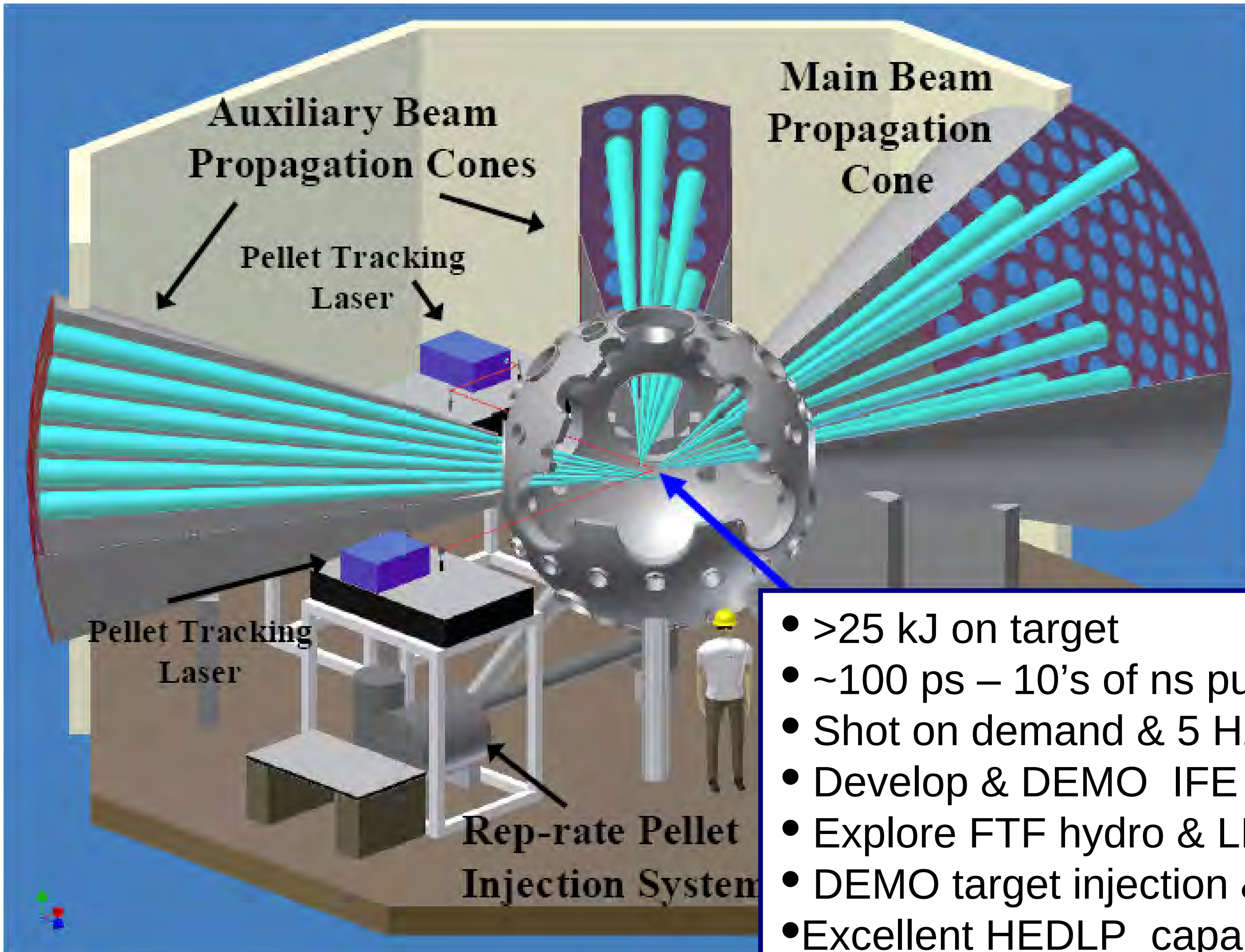
STAGE I is a single laser module of the FTF coupled with a smaller target chamber

Laser energy on target:	25 kJ
Rep Rate:	5 Hz (but may allow for higher rep-rate bursts)
Chamber radius	1.5 m



- Develop and demonstrate full size beamline for FTF
- Explore & demonstrate target physics underpinnings for the FTF

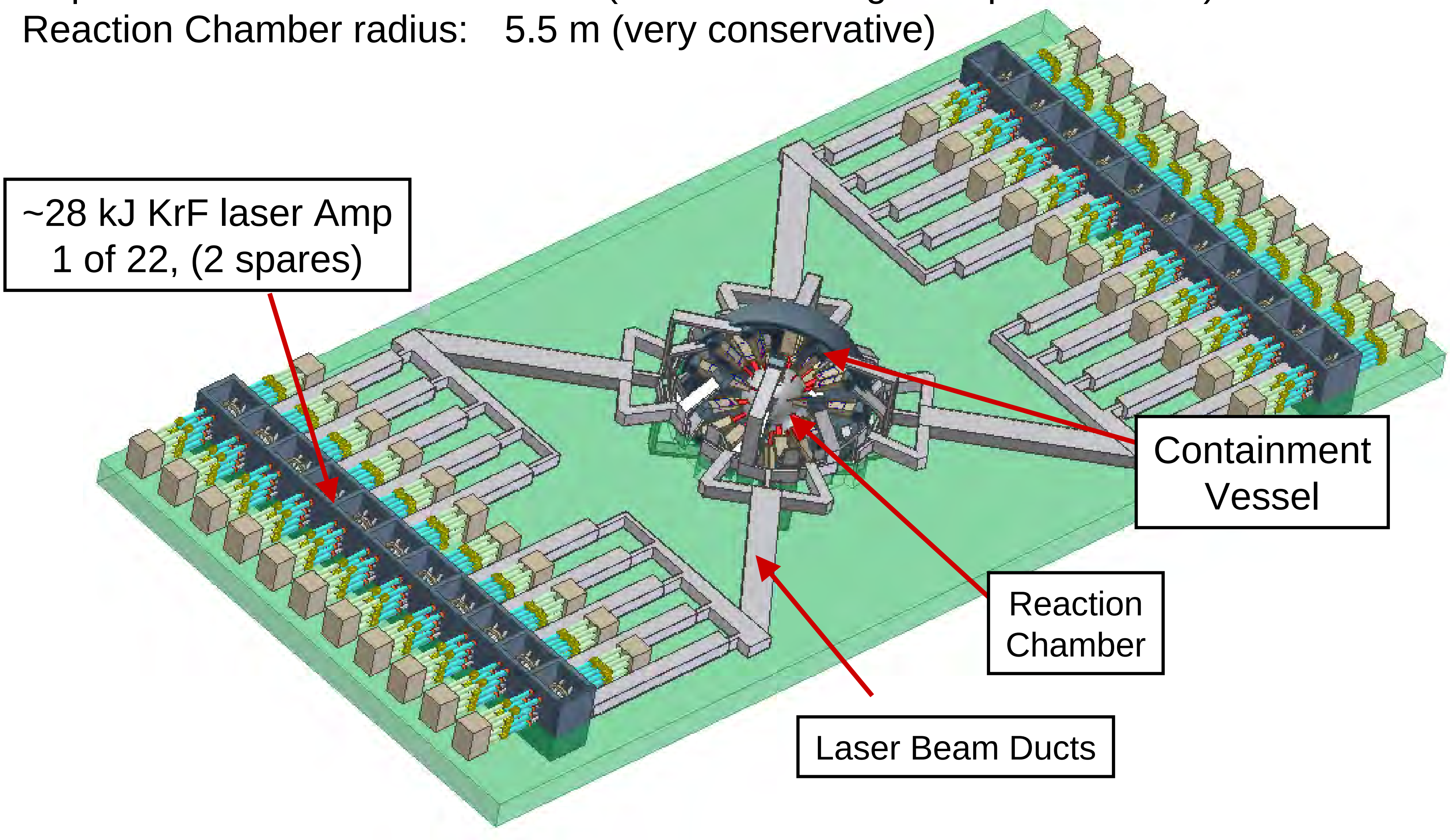
Stage I FTF Target Facility *(aka NRL NexStar)*



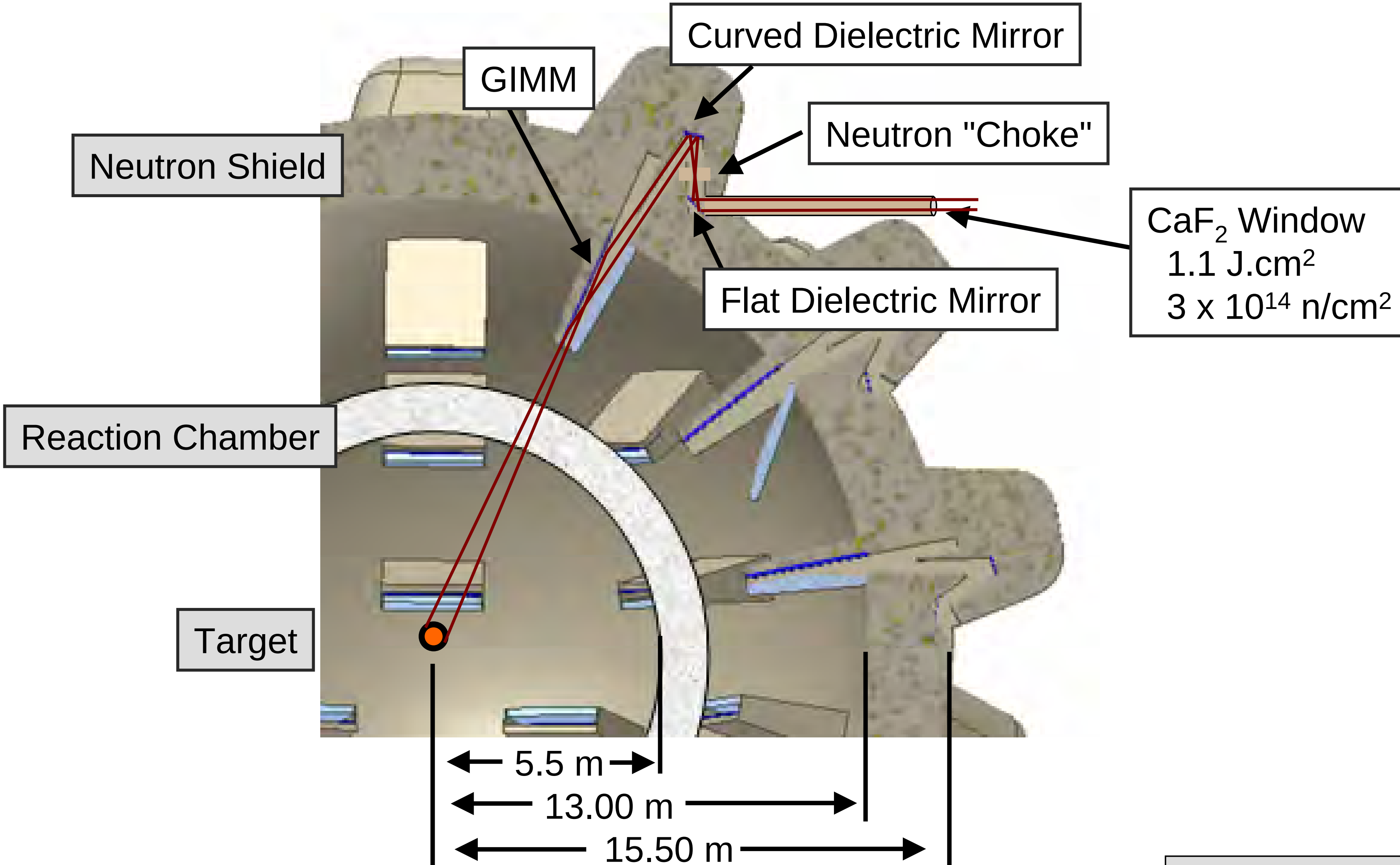
- >25 kJ on target
- ~100 ps – 10's of ns pulses
- Shot on demand & 5 Hz
- Develop & DEMO IFE S&T
- Explore FTF hydro & LPI
- DEMO target injection & engagement
- Excellent HEDLP capability

The Fusion Test Facility (STAGE II)

Laser energy on target: 500 kJ
Fusion power: 150 MW
Rep Rate: 5 Hz (but allow for higher rep-rate bursts)
Reaction Chamber radius: 5.5 m (very conservative)



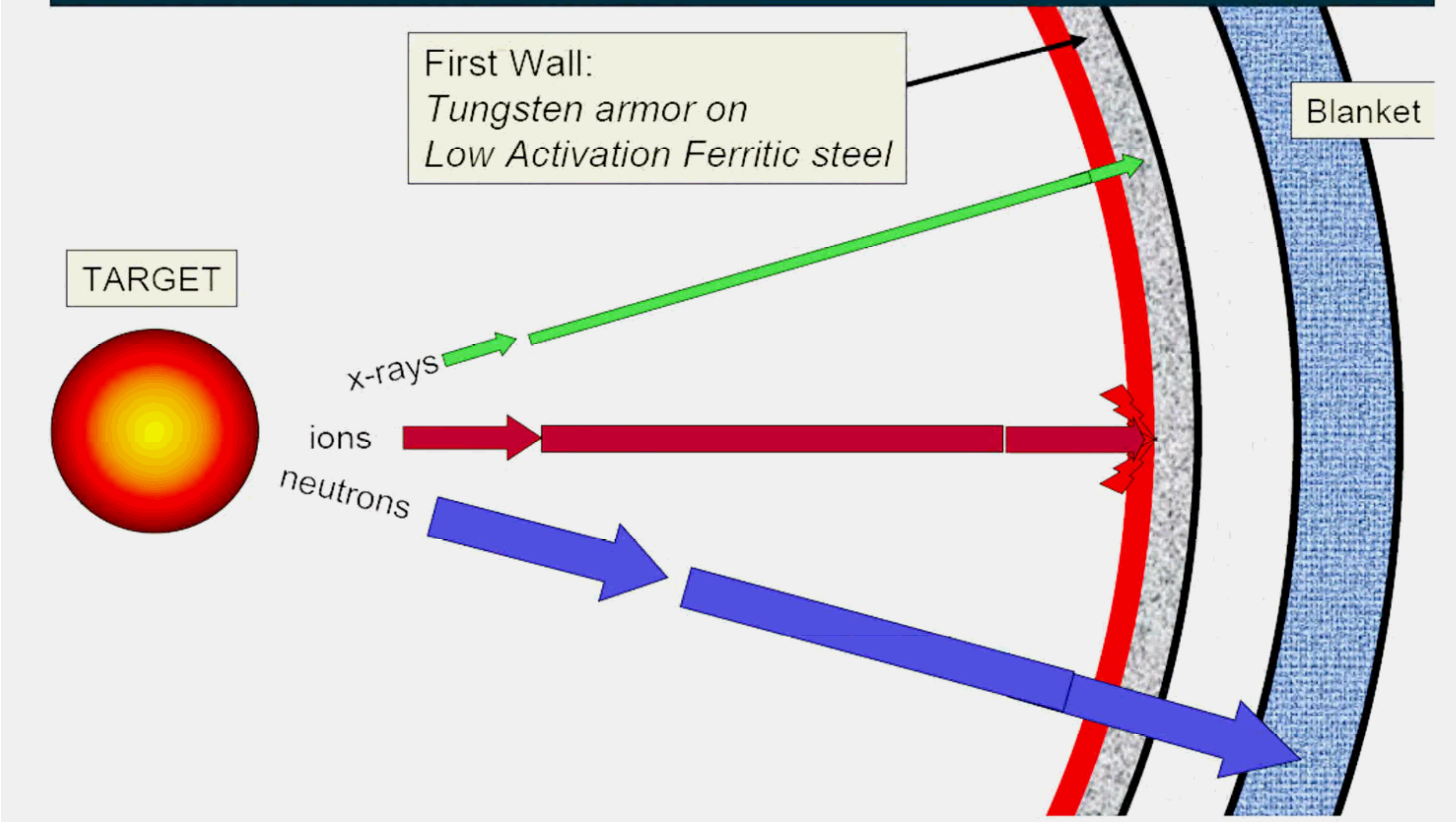
Optical train with GIMM Final Optic



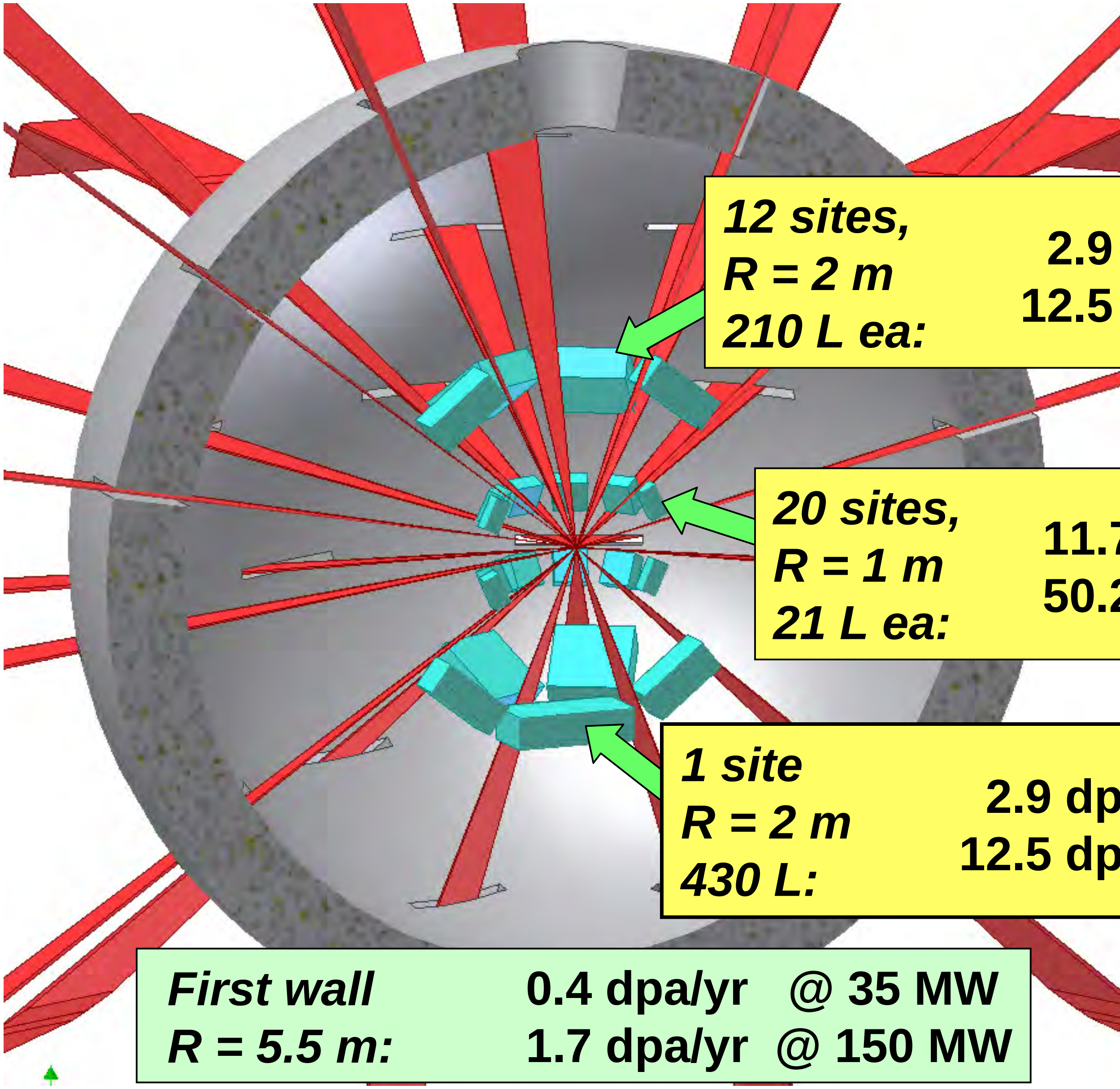
Also evaluating Dielectric Mirror in place of GIMM

M. McGeoch (PLEX)
M. Sawan (Wisc)
L. Snead (ORNL)

We are developing a first wall for the chamber to withstand the steady pulses of x-rays, ions and neutrons from the target.



The FTF can expose materials, components, and structures to power plant level fluxes (> 10 dpa/yr)... and beyond



12 sites,
R = 2 m
210 L ea:

2.9 dpa/yr @ 35 MW
12.5 dpa/yr @ 150 MW

20 sites,
R = 1 m
21 L ea:

11.7 dpa//yr @ 35 MW
50.2 dpa/yr @ 150 MW

1 site
R = 2 m
430 L:

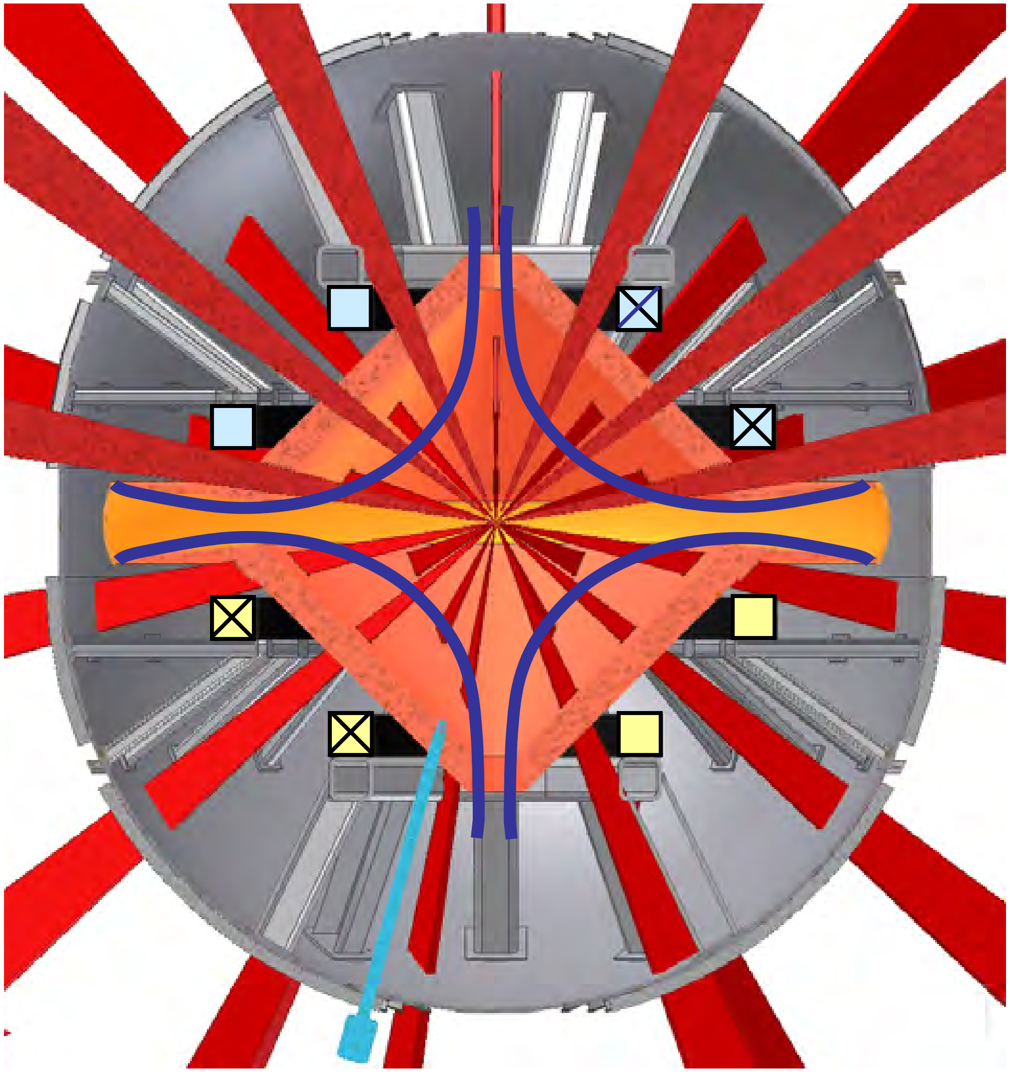
2.9 dpa/yr @ 35 MW
12.5 dpa/yr @ 150 MW

First wall	**0.4 dpa/yr @ 35 MW**
R = 5.5 m:	**1.7 dpa/yr @ 150 MW**

(60 % availability)

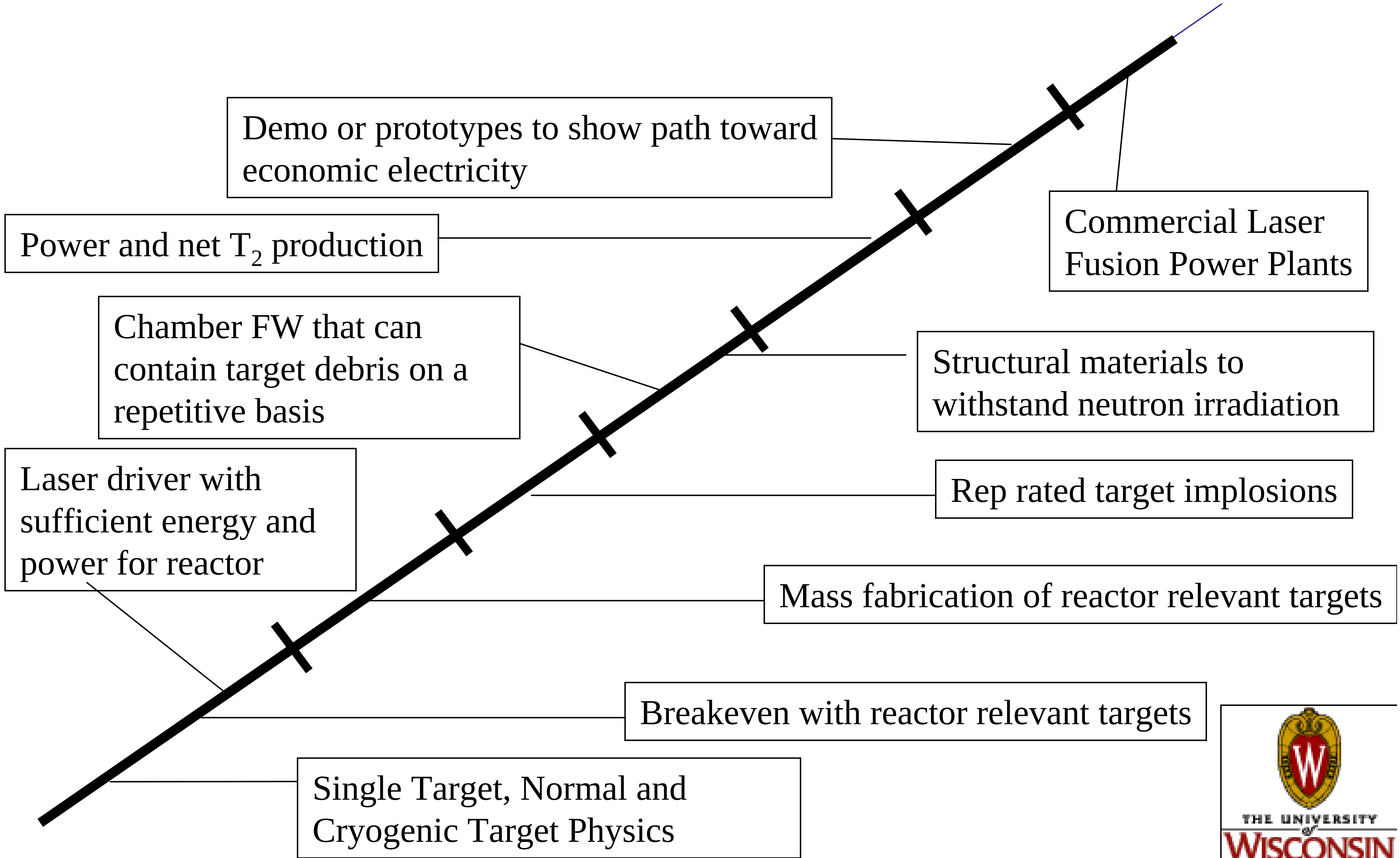
"Magnetic Intervention" offers a way to keep the ions off the wall

1. **Cusp Field (1 T = 10 kG) imposed on chamber**
2. **Ions "radially push" field until stopped by magnetic pressure**
3. **Moving field resistively dissipated in first wall/ blanket**
4. **Ions, at reduced energy *and power,* escape cusp and absorbed in dump**
5. **Basic physics demonstrated in 1979 NRL experiment***
6. **Allows SiC (higher temperature) wall and blanket**



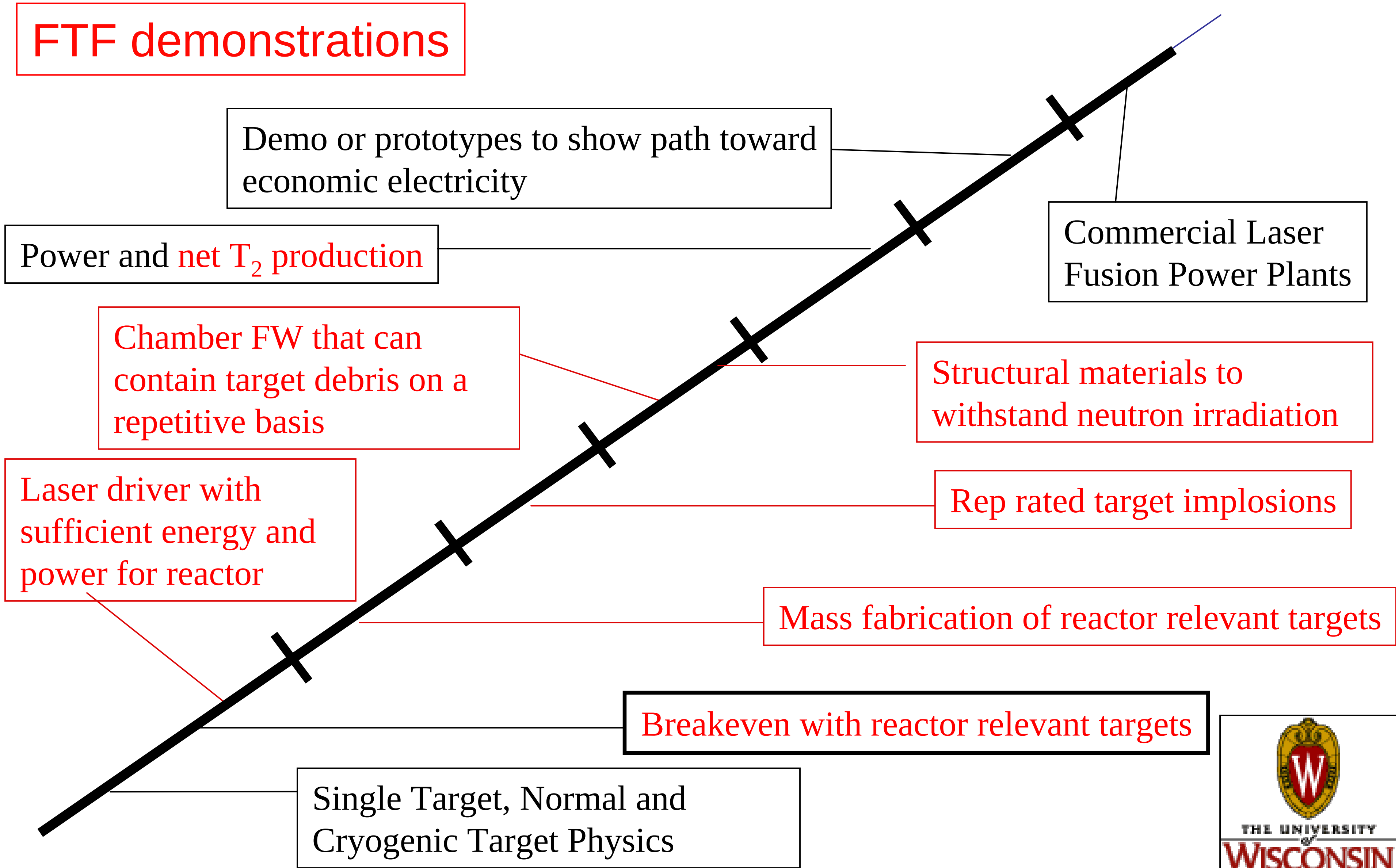
*R. E. Pechacek, *et al*., Phys. Rev. Lett. **45**, 256 (1980).

What Needs to be Done on the Path to a Commercial Laser Fusion Reactor?



THE UNIVERSITY of WISCONSIN MADISON

What Needs to be Done on the Path to a Commercial Laser Fusion Reactor?



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NRL Nike and Electra over next few years will develop FTF S&T underpinnings

Nike Facility →

- 100 shots/day
- 10^{16} W/cm^2 for LPI exp.
- Precision pulse shaping
- FTF diode physics
- DEMO target inject/engage

Electra Facility →

- Solid state HV switches
- >million shot durability
- 1-2 kJ

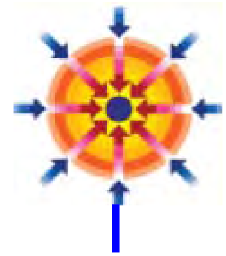
→ Full technical basis for an FTF beamline

FTF path forward

- The NRL laser fusion program is fully committed to exploring and developing the path energy via to a lower drive energy high-rep ignition facility.
- FTF direct drive pellet designs continue to look promising
- Analysis by independent hydrocodes underway
- There is plenty to be done in science and technology
- We continue to invite and expect contributions by the other IFE/ICF research groups

Overview: Approach to Heavy Ion Fusion Science*

Presented by B. Grant Logan
on behalf of the
Heavy Ion Fusion Science-Virtual National Laboratory**
Presented to:
IFE Science and Technology Strategic Planning Workshop
San Ramon, California
April 24-27, 2006



Heavy ion beams

- Historical background and vision for heavy ion fusion
- Current status of heavy ion fusion science research
- Near term plans, and technical issues for HIFS research for HEDP and future IFE.
- Long range IFE vision: 20 year science campaign plan, funding needs, technical challenges

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.
** HIFS-VNL: A collaboration between Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory, USA.

HIFS-VNL perspective for this workshop:

- **No current IFE approach, even HIF, has a knowledge base sufficient to justify a billion-dollar IFE fusion test facility →it is premature to down-select to a single IFE approach now.**

- **Heavy ion fusion (HIF approach) offers a unique set of advantages and challenges for HEDP science as well as for IFE.**

- **The combination of NIF plus moderate-scale new facilities could address many of the critical scientific issues for several approaches to IFE.***

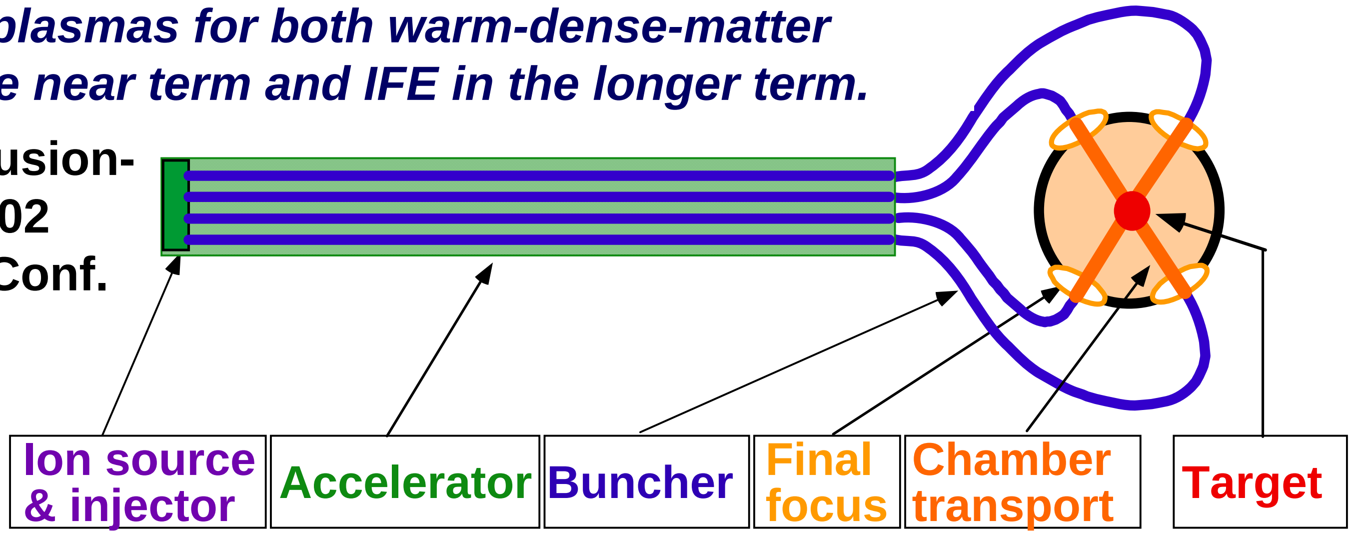
The IFE community should work together to address critical issues for IFE science and technology in an ecumenical fashion.

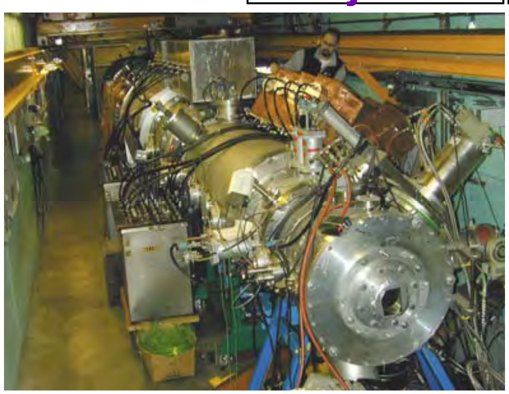
***See NIF-IFE Workshop Feb. 1994, and IAEA-CN-60 B-P15, Seville Conference Proc. IAEA, 1996.**

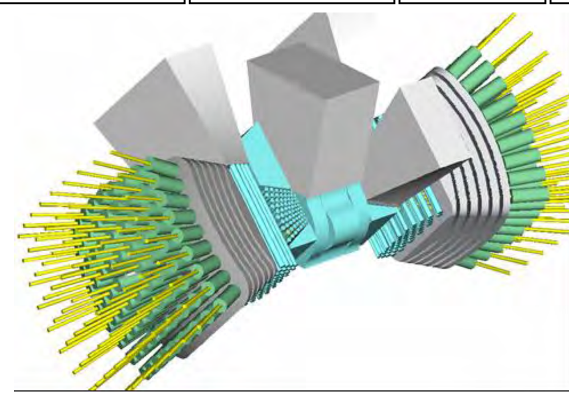
Through 2002, the heavy ion fusion program pursued research on induction linacs, liquid-protected chambers, and indirect-drive targets for IFE.

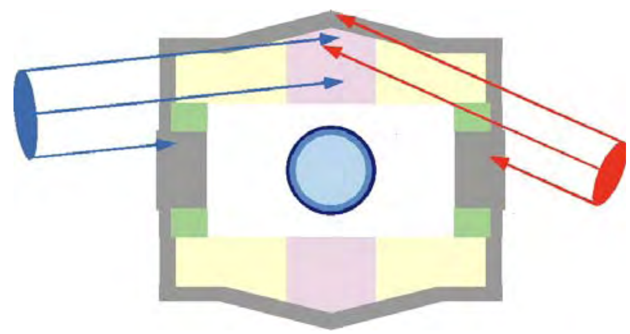
Since 2003 we've pursued beam compression and focusing in plasmas for both warm-dense-matter targets in the near term and IFE in the longer term.

Heavy Ion Fusion-Concept- 2002 Snowmass Conf.





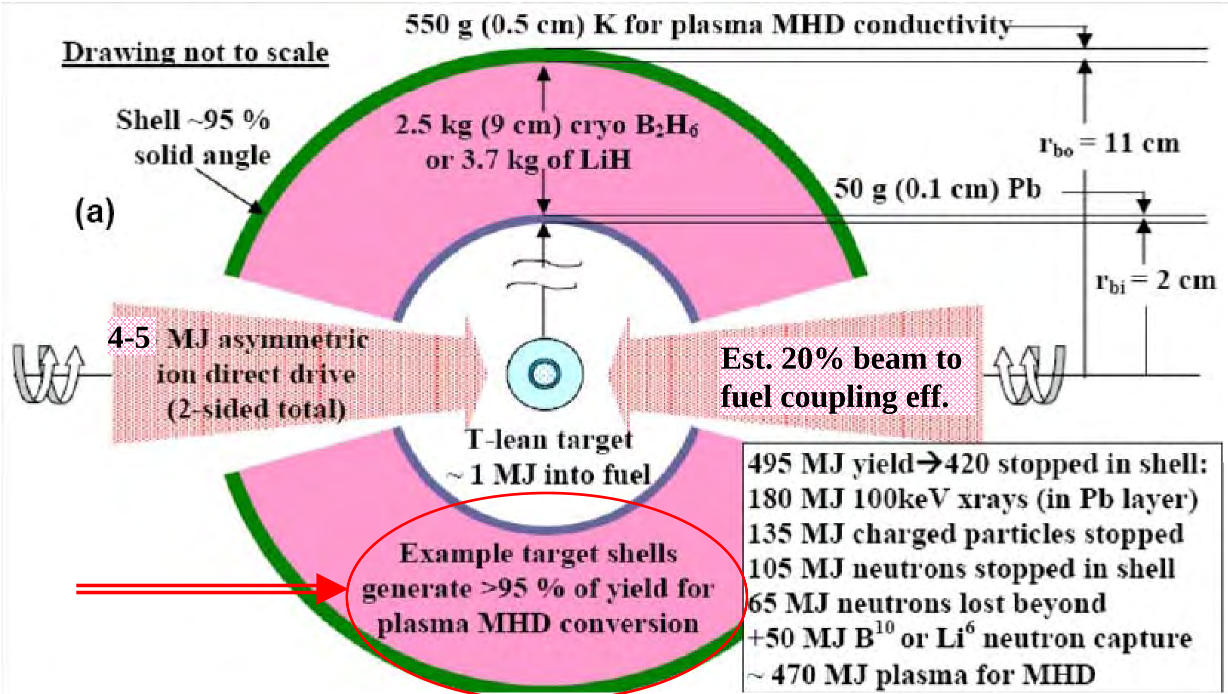




Beams at high current and sufficient brightness to focus

Long lasting, low activation chambers that can withstand 300 MJ fusion pulses @ 5 Hz

High gain targets that can be produced at low cost and injected



[2] B. Grant Logan "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD Conversion" Fusion Engineering and Design 22, 151 (1993)

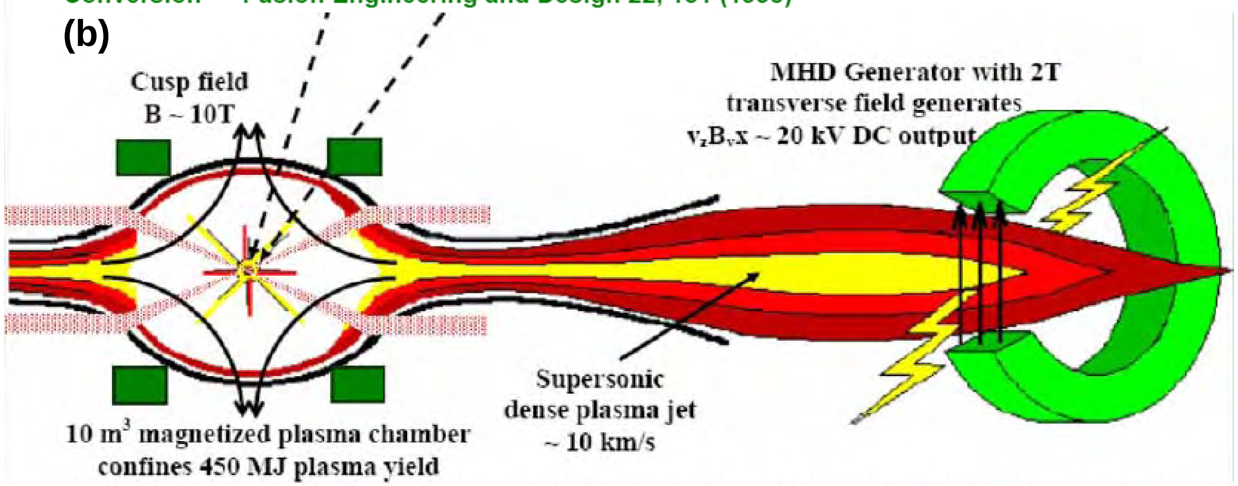


Figure 4: (a) Example target shell for efficient conversion of T-lean target output into 1 to 2 eV dense plasma for direct MHD conversion. All shell materials condense and recycle (Rankine cycle).
(b) Schematic of the CFAR MHD scheme (adapting the old 1992 CFAR Logo!)--no detailed design yet.

New studies of heavy ion direct drive point to a unique IFE vision: potentially higher coupling efficiency enables direct conversion

Note key facts about the marriage of T-lean targets (Max Tabak 1996) to CFAR MHD conversion:
(1) Most T-lean target yield can be captured for direct plasma MHD conversion, even down to 1MJ–scale DEMO drivers.
(2) Plasma conductivity is 10^5 times greater at 25,000 K than at 2500 K→ the extractable MHD conversion power density ~σu^2, where u~10km/s is the plasma jet velocity, is >30 times the power density of steam turbine generators[2].
→As a consequence, the CFAR Balance of Plant *cost* can be much lower, < $ 80 M/ GWe!

Reasons why many past reviews supported heavy ion fusion ***still apply***:

1) HIF builds upon a high-energy particle accelerator experience base for efficiency, pulse rate and durability.

2) Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron, and gamma radiation.

3) Thick-liquid protected target chambers with 30-year plant life may avoid the need for a long and costly fusion materials development program.

4) Several heavy ion power plant studies have shown attractive economics (competitive CoE with nuclear plants) and environmental characteristics.

5) HIF target physics benefits from much of the target physics data being generated by NNSA.

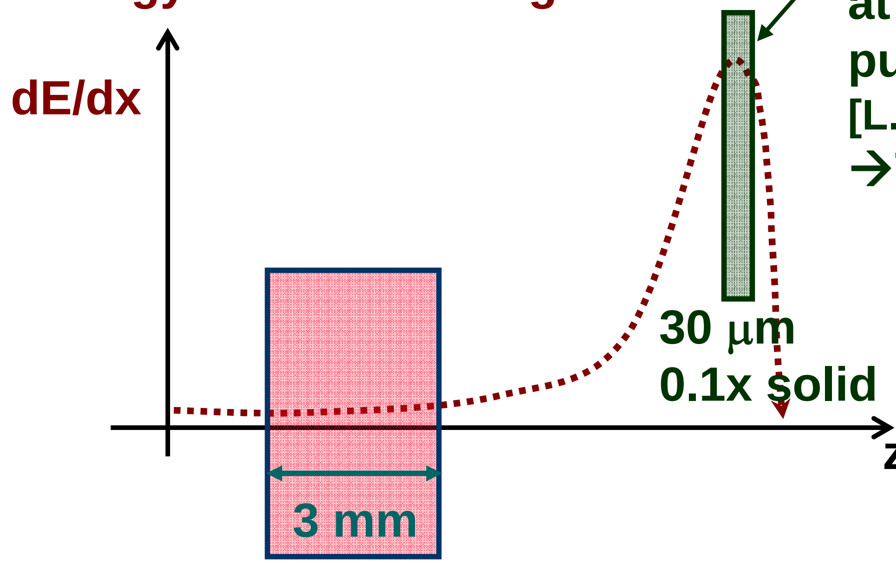
Current status of heavy ion fusion science research

What is the present HIFS Program status?

- Compressed intense heavy ion beams in neutralizing background plasma in NDCX-I: 150 ns to 3 ns FWHM.
- Begun heavy-ion driven isochoric target heating experiments to 1 eV in joint experiments with GSI, Germany, to develop HEDP diagnostics.
- Unique diagnostic measurements of electron cloud effects on intense heavy-ion beam transport in both quadrupole and solenoid magnets.
- Computer simulation models that match the experimental results in both neutralized beam compression and e-cloud studies.
- ATA accelerator equipment sufficient for 3 to 6 MeV NDCX-II next step for both warm dense matter and ion direct drive target physics experiments.
- In-house capability to run HYDRA code for NDCX target design support.
- Basic principles of vortex control (tangential injection and ejection) demonstrated at UCB→ flexible free-liquid-surface geometry control.

The HIFS-VNL pursues a unique approach to warm dense matter physics driven by intense, compressed ion beams

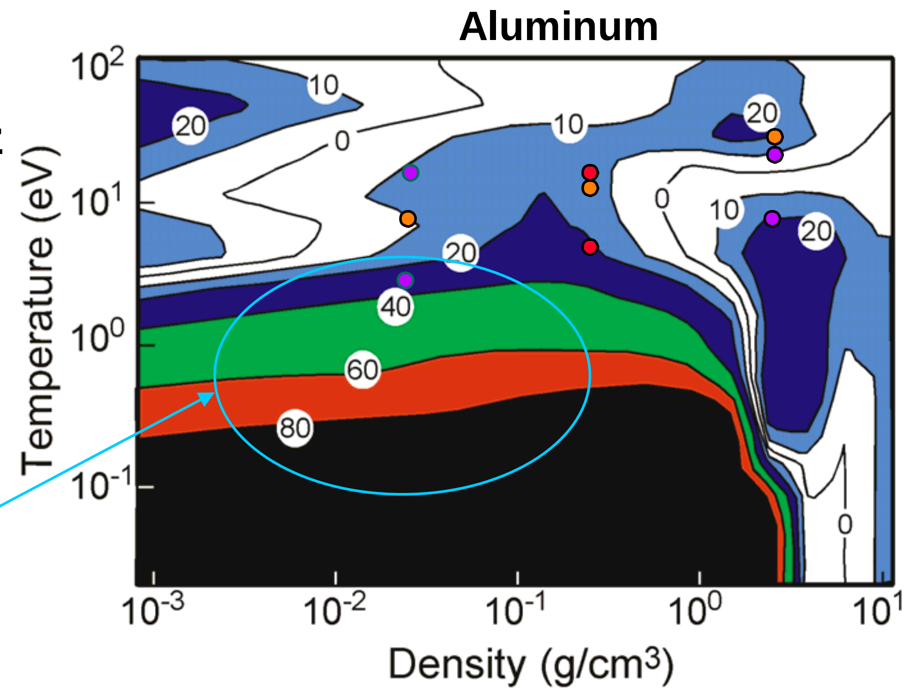
Ion energy loss rate in targets



Maximum dE/dx *and* uniform heating at this peak require short (~ 1 ns) pulses to minimize hydro motion.
[L. R. Grisham, Phys. Plasmas 11, 5727(2004)].
→Te ~ 0.5 eV in NDCX-I by FY09,
Te > 1 eV in NDCX-II by FY10+

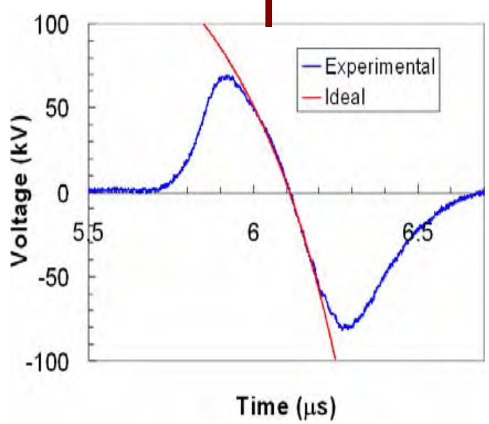
GSI: 40-100 GeV heavy Ions→ thick targets→ Te ~ 1 eV per kJ

Dense, strongly coupled plasmas @ 10^{-2} to 10^{-1} *x* solid density are potentially interesting areas to test EOS models (Numbers are % disagreement in EOS models where there is little or no data)
(Courtesy of Richard W. Lee, LLNL)

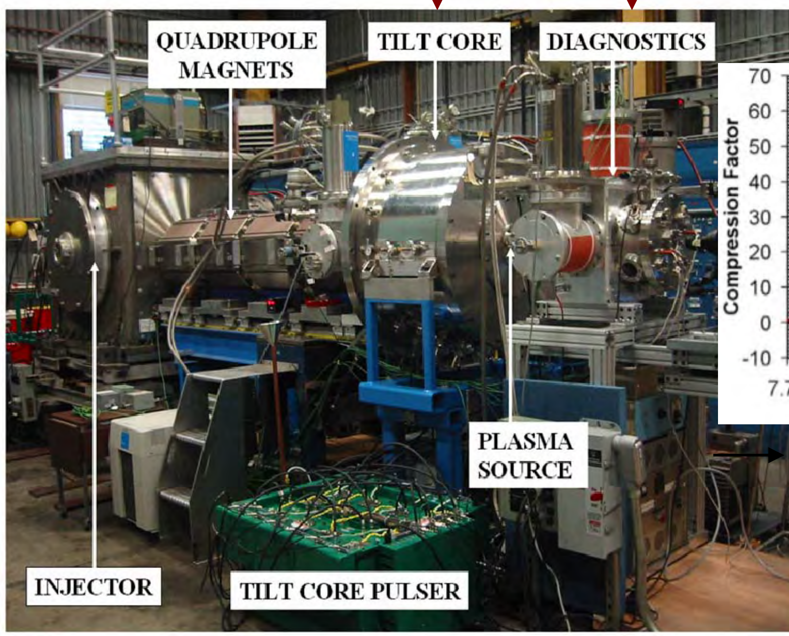


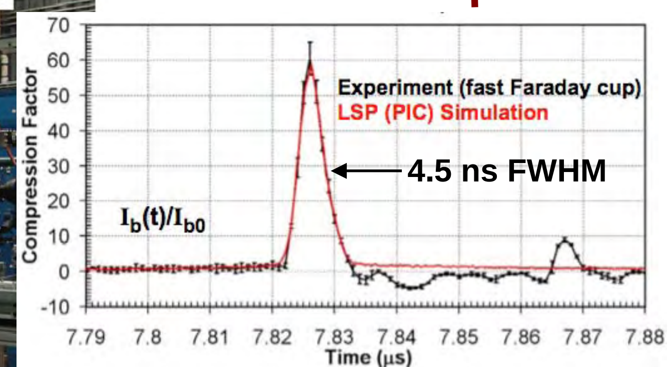
Dramatic progress in compression of neutralized beams in NDCX-I enables both Warm Dense Matter and planar direct drive experiments.

Induction core impresses head-to-tail velocity ramp ("tilt") on 200-ns slices of injected 300 keV K^+ ion beam, compressing the slices to 3 ns at diagnostic end, *consistent with particle-in-cell simulations*



Induction waveform



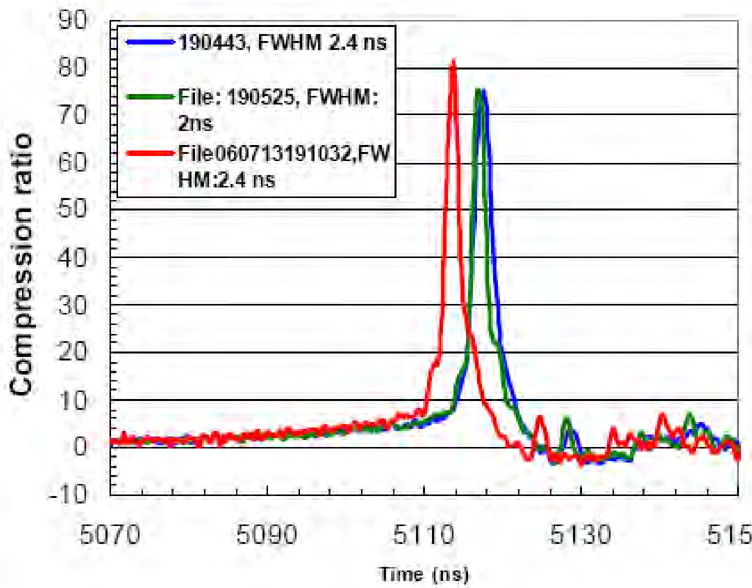


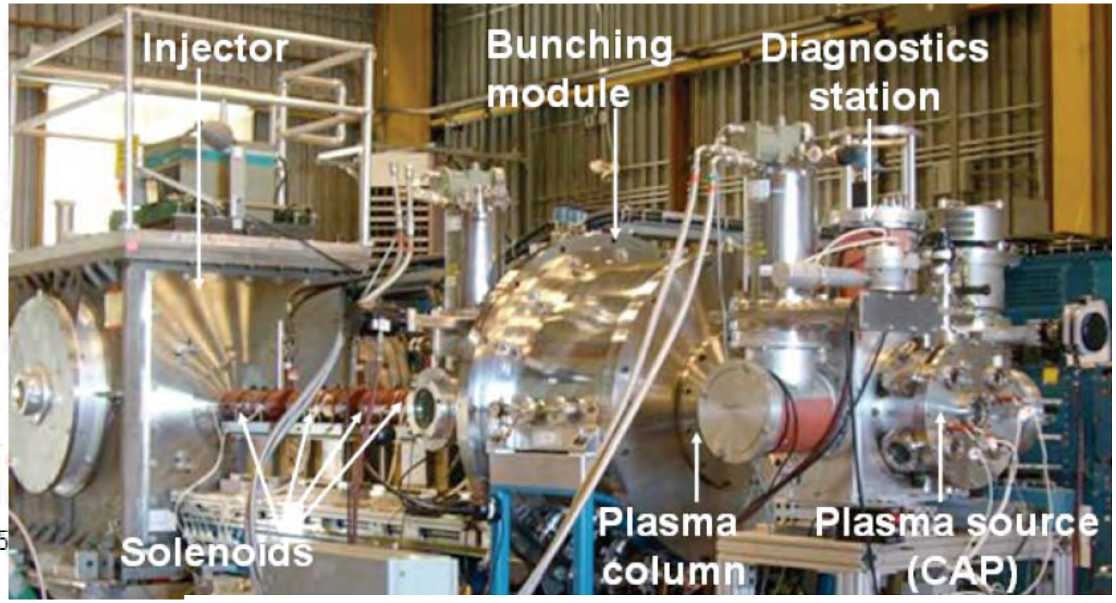
End beam current with velocity ramps comparing data with LSP simulation

The Neutralized Drift Compression Experiment (NDCX-I) began operation in Dec 2004

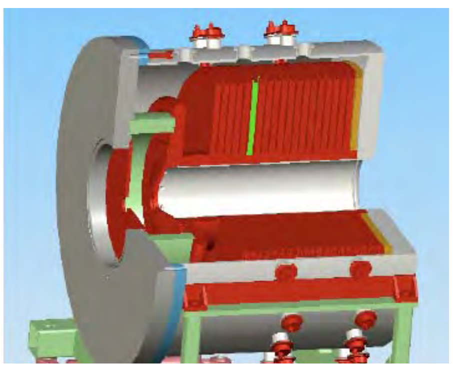
The neutralized drift compression experiment (NDCX-I) continues to improve longitudinal compression of intense neutralized ion beams

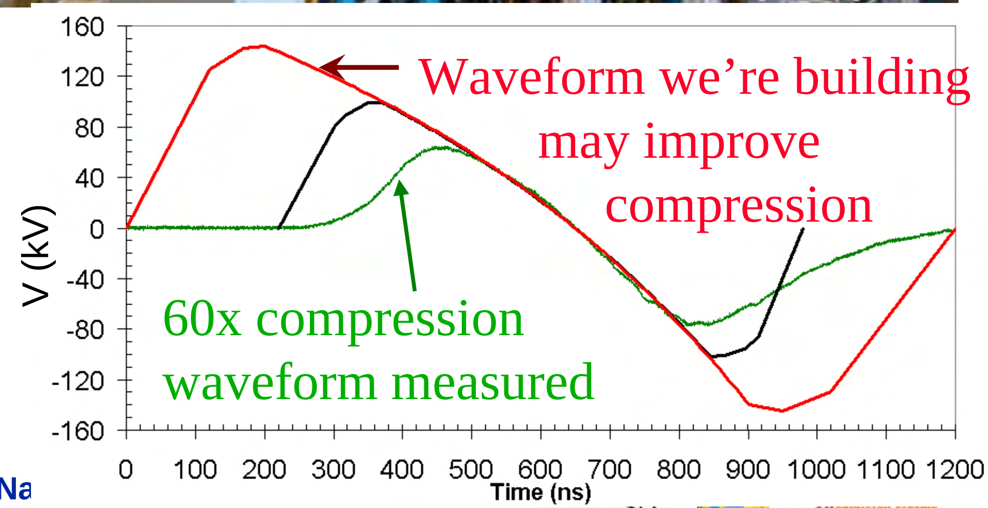
Shorter pulses (2.4 ns) obtained with new Ferro-electric plasma source





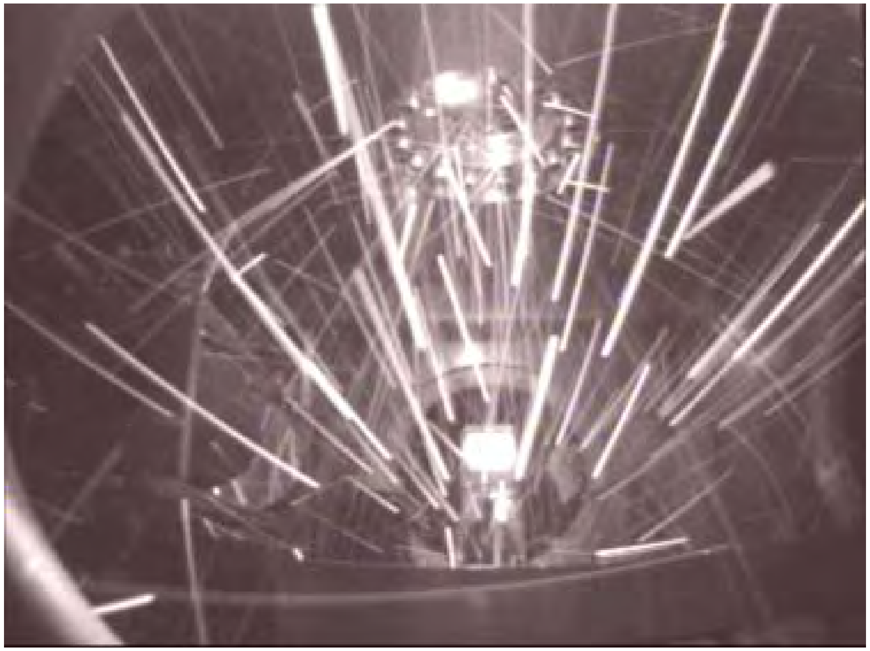
Simulations predict higher compression with new induction bunching module to be installed this summer

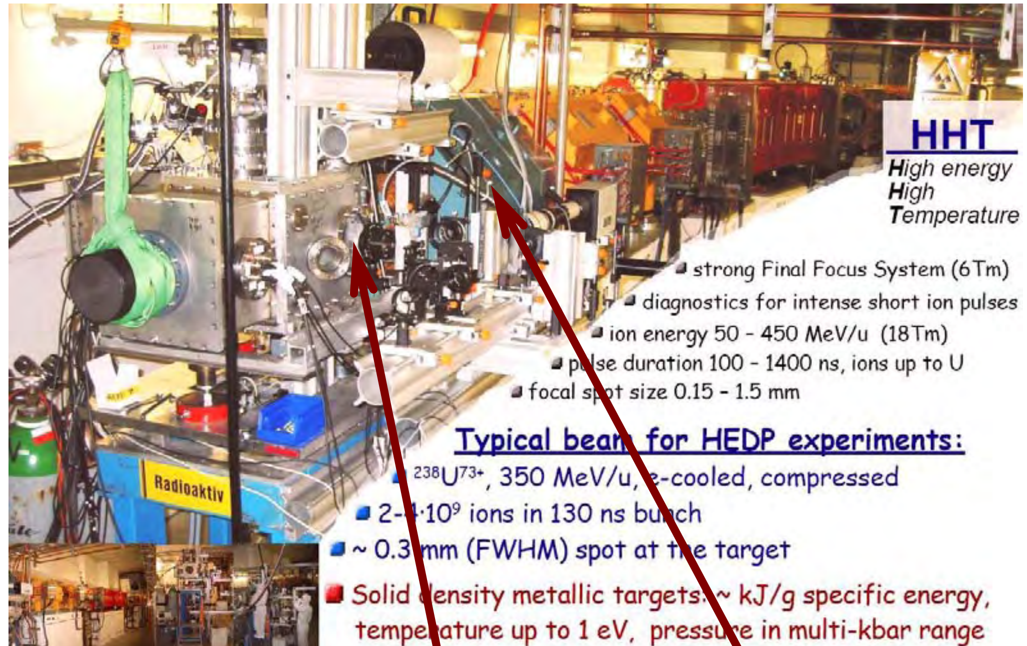




Joint experiments with GSI are developing diagnostics and two-phase EOS models for isochoric heating & expansion relevant to indirect drive HIF target radiators, and to droplet formation.

(Frank Bieniosek –see also John Barnard's talk tomorrow)



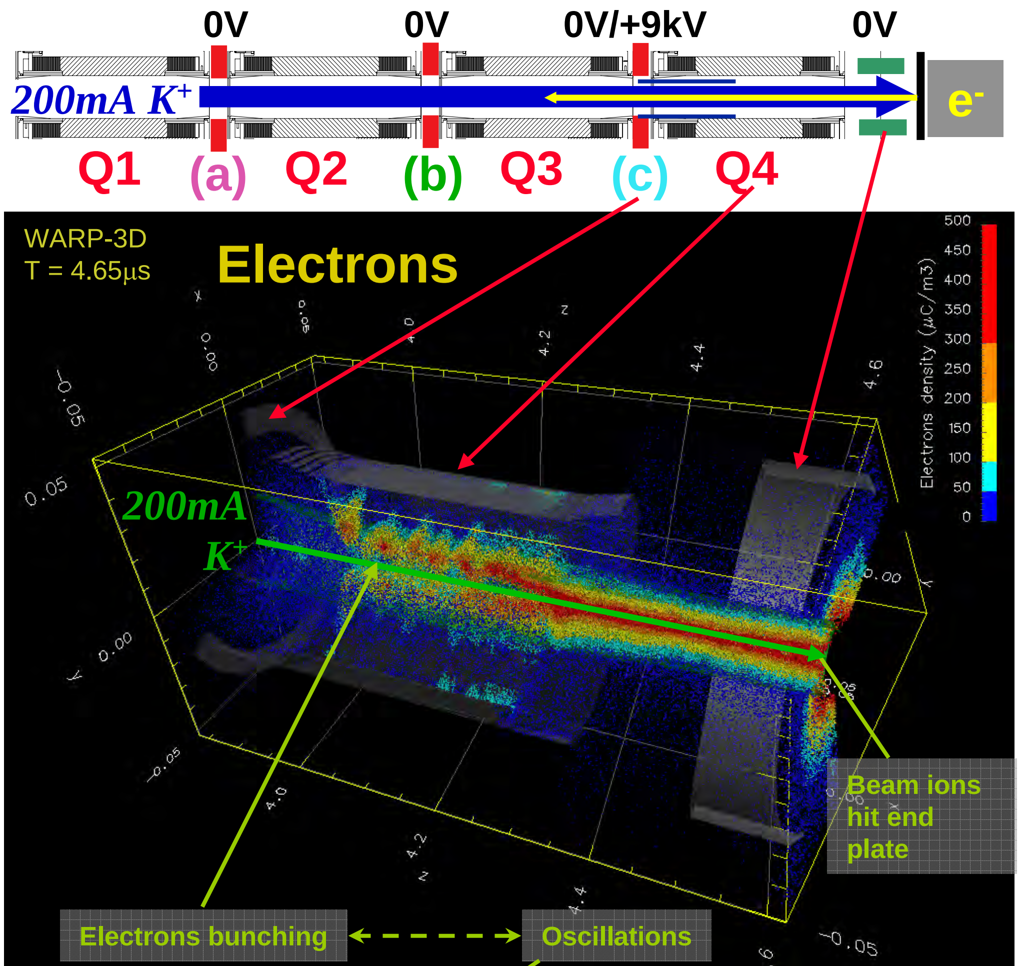


Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 100 ns, 10 J heavy ion beam to 1 eV in joint experiments at GSI, Germany

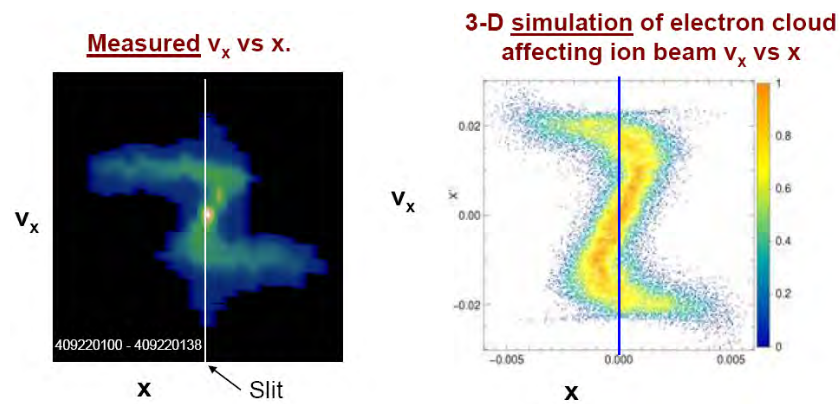
Final focus magnets

Optical diagnostic windows need to be periodically cleaned of target debris and sometimes replaced.

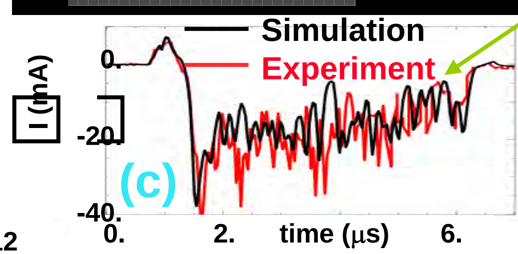
High Current Experiment (HCX) benchmarks world-leading modeling capability for electron/gas cloud effects



←Large e-clouds are allowed into four HCX magnetic quadrupoles from the end to enhance measurements of e-cloud effects in short distances.



Electron and gas cloud modeling critical to all high current accelerators, including HEP: LHC, ILC …and future HEDP/fusion drivers: NDCX-II, IB-HEDPX

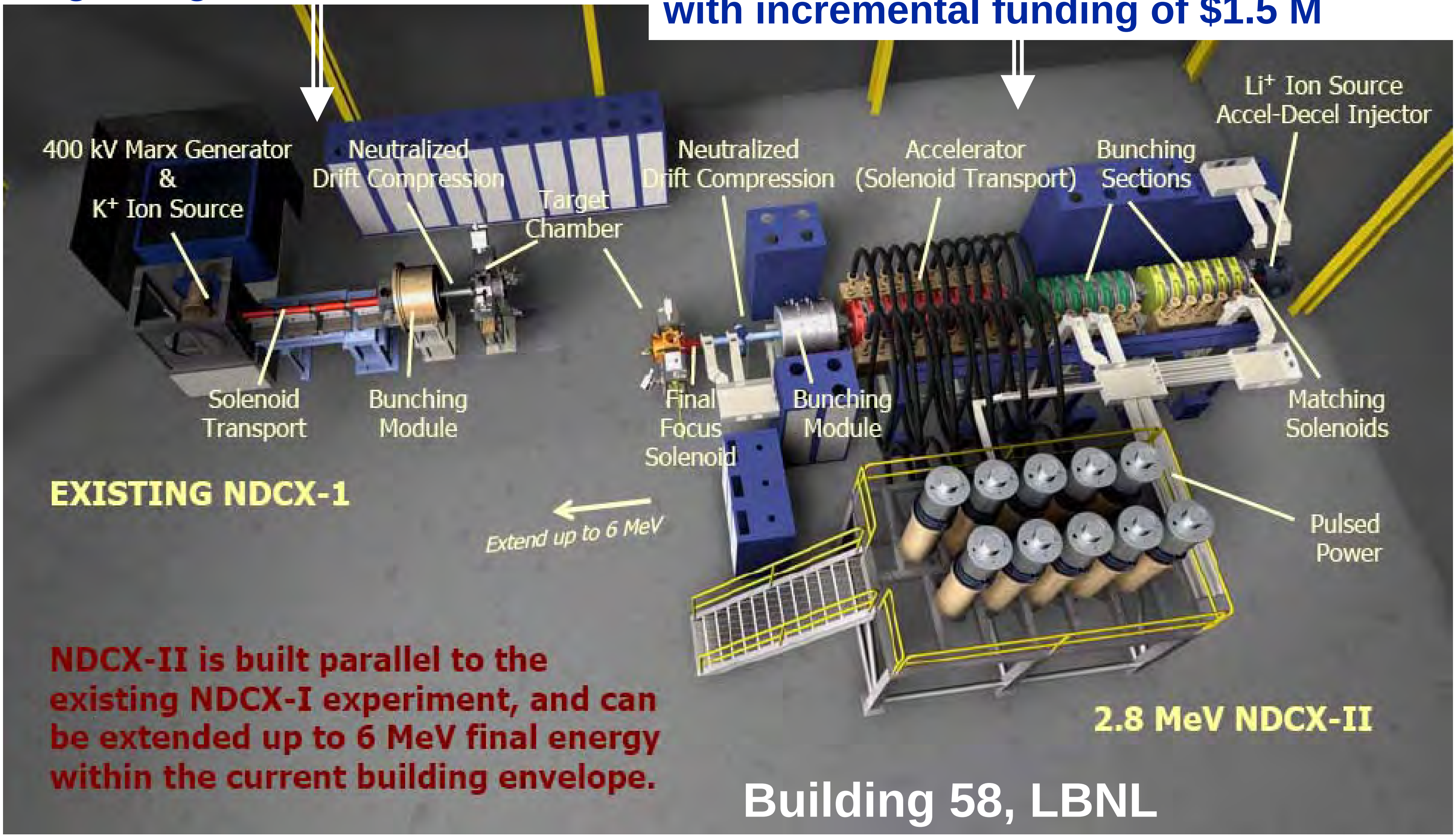


6 MHz oscillations in (C) in simulation AND experiment

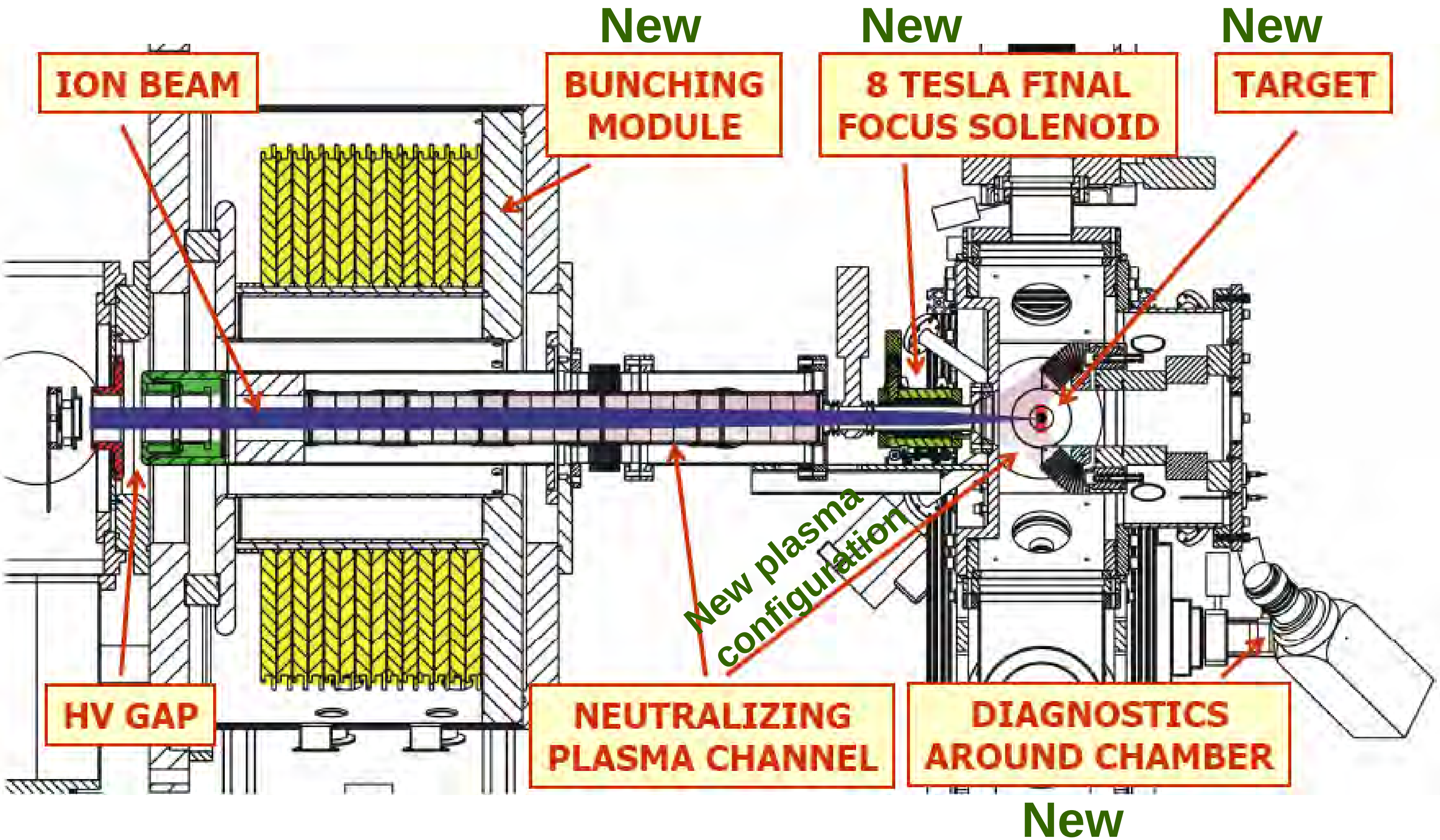
Near term plans, and technical issues for HIFS research for both HEDP and future IFE.

NDCX-I is being upgraded this year for first mm-scale warm dense matter experiments beginning in FY08.

NDCX-II, using ATA components for more beam intensity and more uniform deposition, could be completed by FY10 with incremental funding of $1.5 M

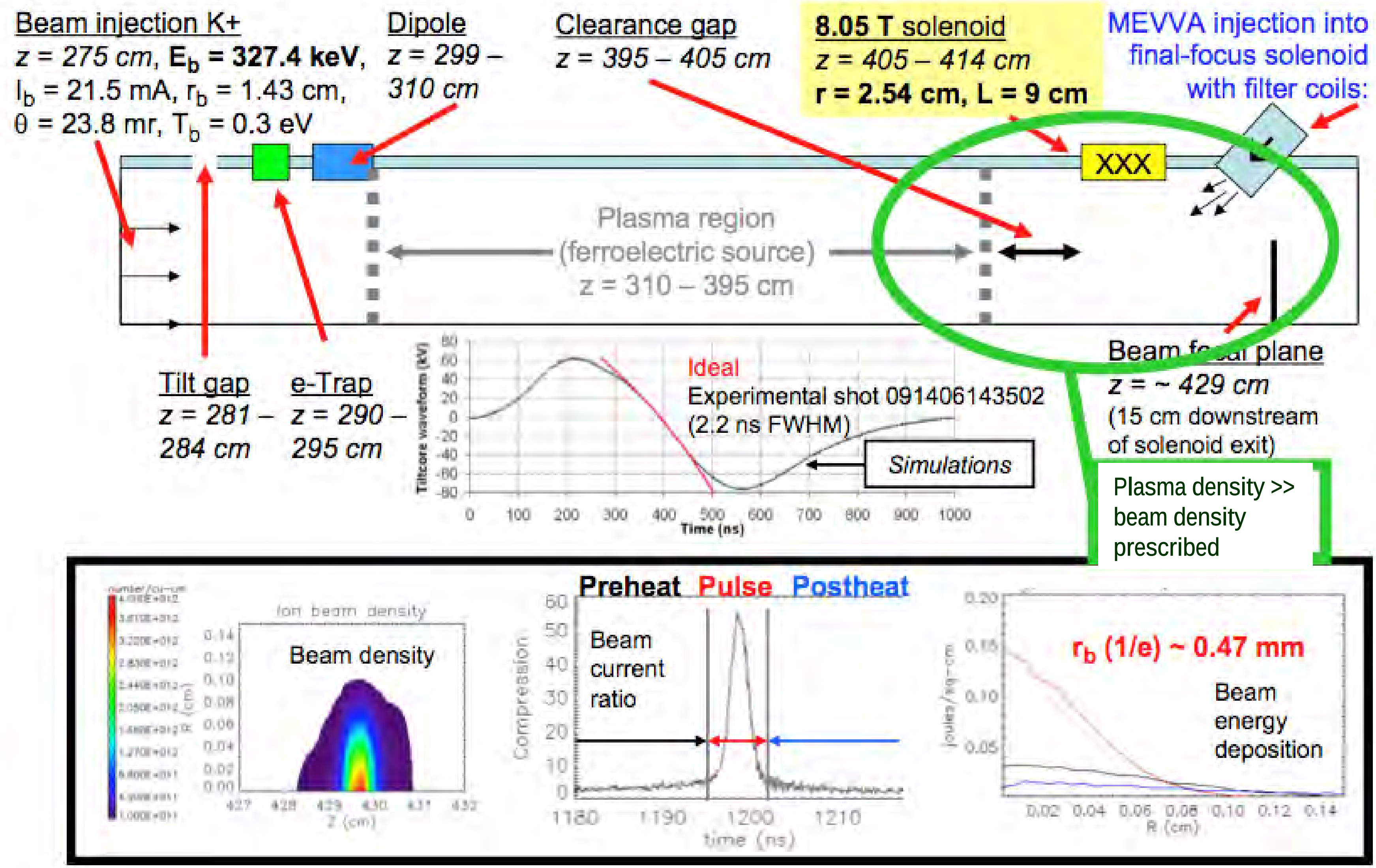


Improving NDCX-I for FY08-09 warm dense matter experiments



(See Peter Seidl for details)

Simulations (Adam Sefkow, PPPL) show smaller NDCX-I focal spots with high field focusing solenoid to be installed later this year



With new improved bunching module to be installed later this year, plus a higher field 15T focusing magnet in FY09, NDCX-I is predicted to support >0.5 eV target conditions with 2 ns pulses

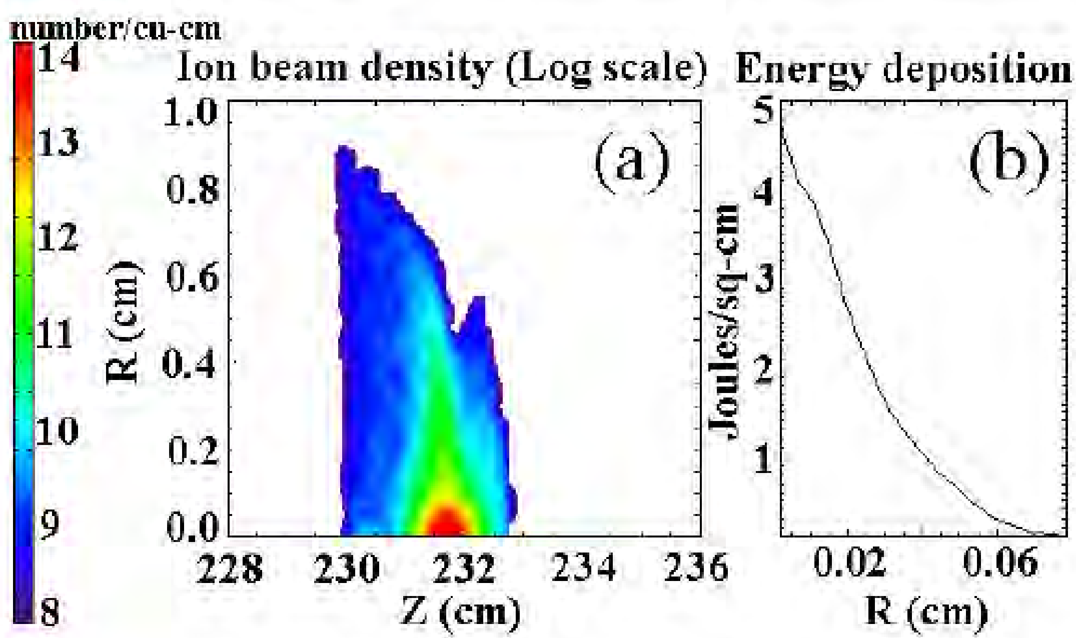
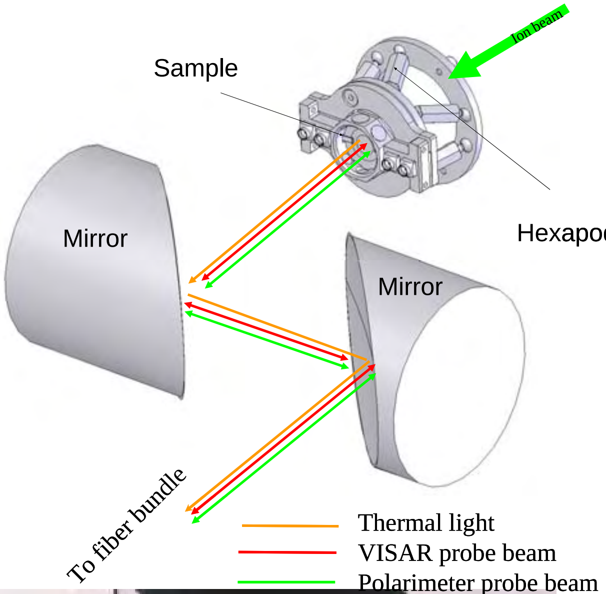


Fig. 6. Ion beam properties at the simultaneous focal plane (within a 150 kG final-focus solenoid): (a) density (log scale); and (b) radial profile of cumulative energy deposition through the focal plane.

Actual achievable NDCX-I intensity for WDM targets in FY09 will range between 0.15 J/cm^2 (previous slide) and this simulation of best possible case ~ 4 J/cm^2 . Target temperature ~ 1 eV/ per J/cm^2 for NDCX-I ions, and neglecting hydro motion (John Barnard's model predictions)

Initial NDCX-I Target diagnostics (see Frank Bieniosek)

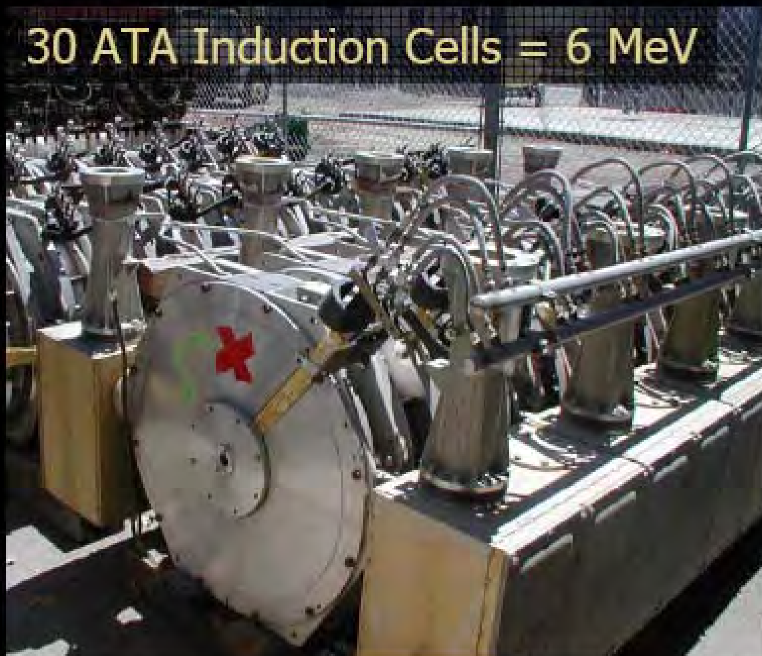
- **Fast optical pyrometer**
  - **Similar to GSI pyrometer, improved for faster response (~1 ns) and greater sensitivity**
  - **Temperature accuracy 5% for T>1000 K**
  - **Position resolution about 400 micron**
  - ***Parts are being ordered – to be assembled in FY07***

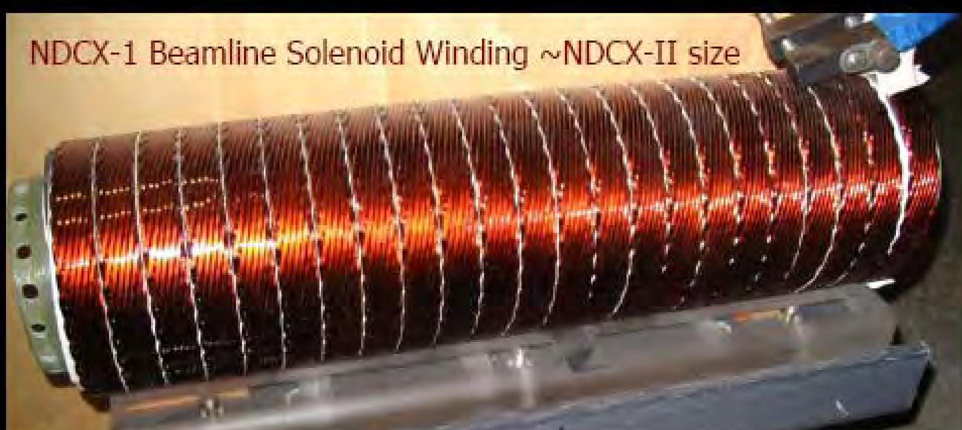


- **Fiber-coupled VISAR system – *now under test***
  - **Martin Froescher & Associates**
  - **Sub-ns resolution**
  - **1% accuracy**

- **Hamamatsu visible streak camera with image intensifier**
  - **Sub-ns resolution**
  - ***arrived Feb. 2007***

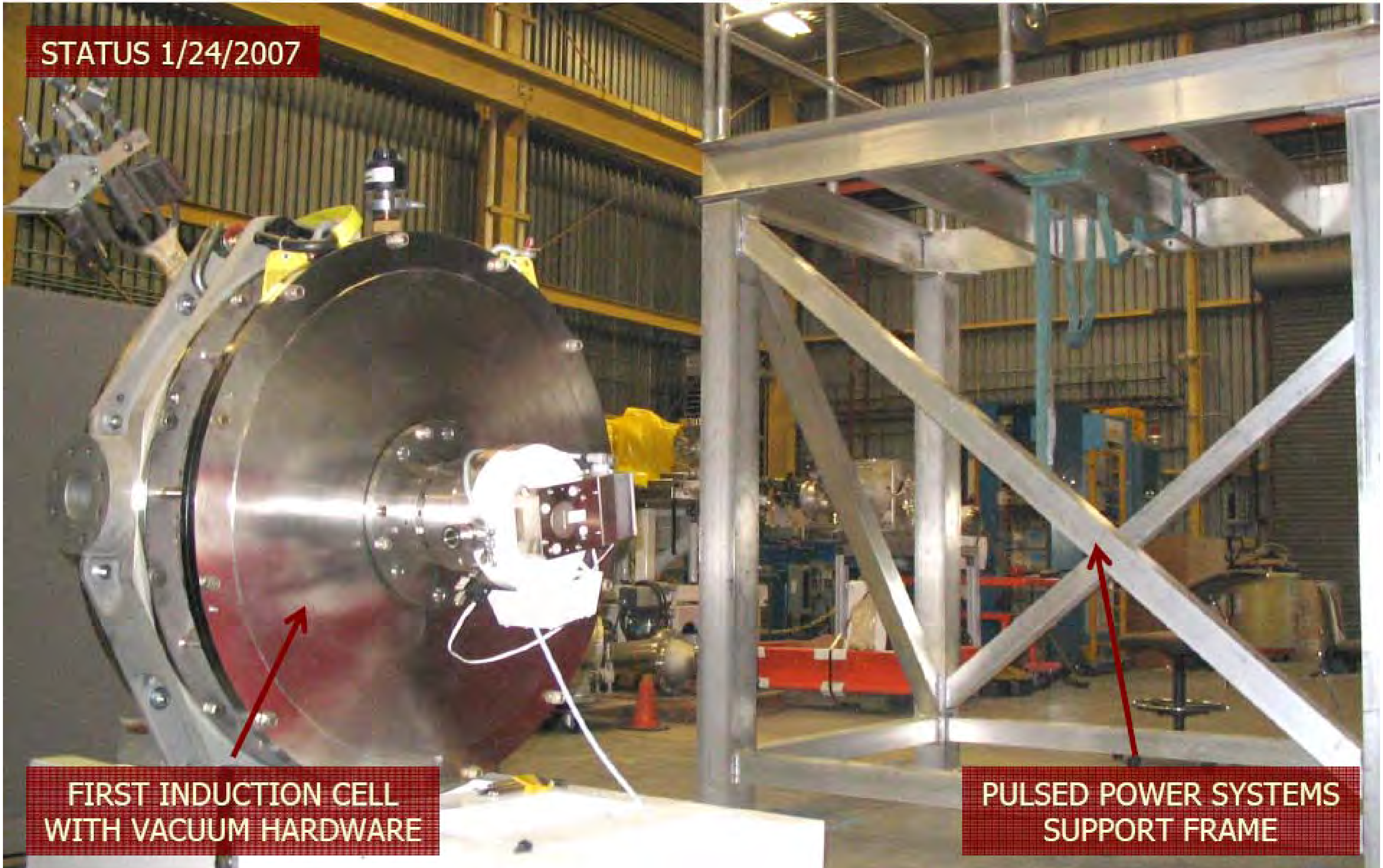
LLNL has donated 30 surplus ATA induction modules now located at LBNL- sufficient for NDCX-II





- We have shipped hardware for 30 induction cells to LBNL.
- We are building a high-field pulsed solenoid to fit into an ATA induction cell for tests.
- Hardware for two cell units has been refurbished for testing.

NDCX-2 TESTSTAND IS CURRENTLY UNDER CONSTRUCTION TO VERIFY CELL PERFORMANCE AND TO TEST HIGH FIELD SOLENOID



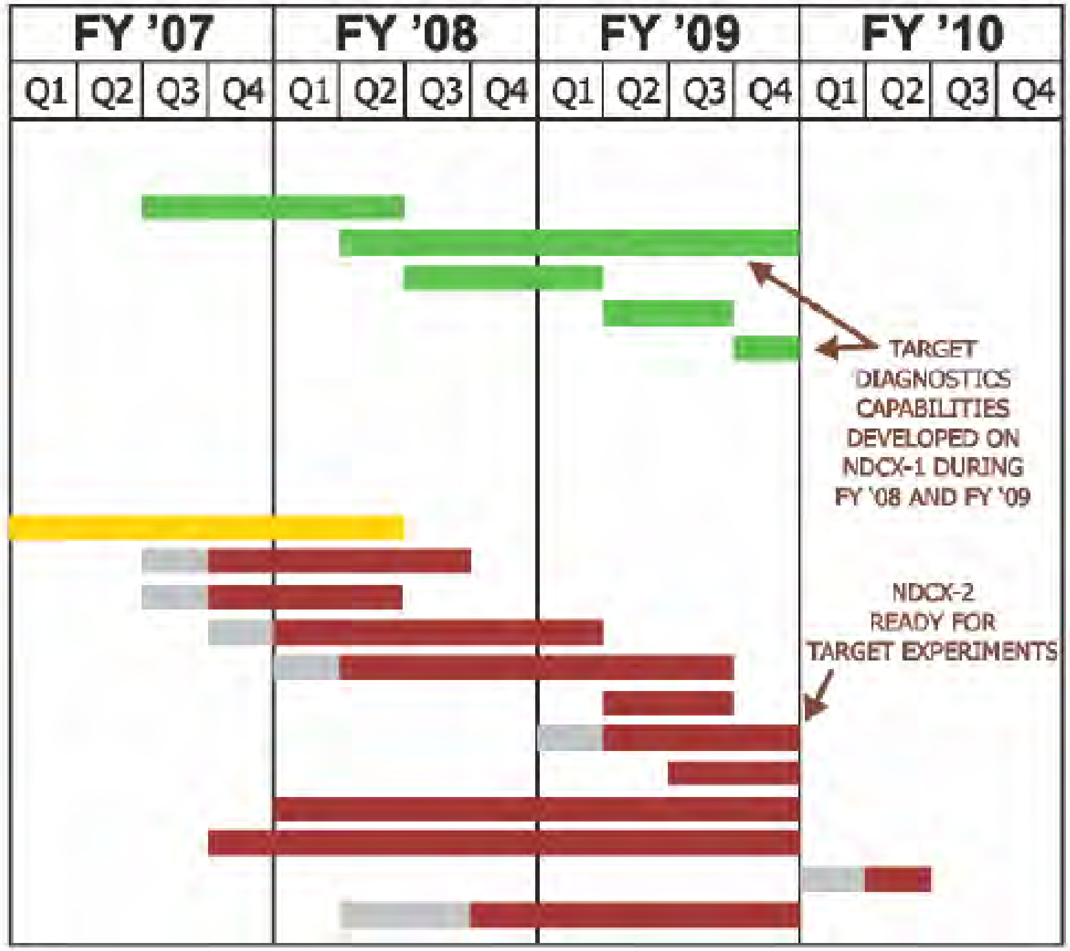
POSSIBLE NDCX-2 SCHEDULE
(PRESIDENT'S BUDGET DOES NOT CURRENTLY SUPPORT NDCX-2 CONSTRUCTION)

NDCX-1

(1) COMPRESSION IMPROVEMENT CAMPAIGN
(2) TARGET EXPERIMENTS
(3) TIME DEPENDENT FOCUSING EXPERIMENTS
(4) PLASMA SOURCE IMPROVEMENT
(5) HYDRO EXPANSION AND TARGET TEMPERATURE MEASUREMENTS

NDCX-2

(1) CONCEPTUAL DESIGN
(2) INJECTOR
(3) INJECTOR SOLENOIDS
(4) PRE-BUNCHING SECTION
(5) ACCELERATOR
(6) DRIFT BUNCHING MODULE (EXISTING)
(7) DRIFT COMPRESSION
(8) TARGET CHAMBER INCL. MAGNET (EXISTING)
(9) CONTROLS
(10) SUPPORT HARDWARE
(11) DOUBLE PULSING HARDWARE
(12) SUPERCONDUCTING FF SOLENOID



Selected major technical challenges for both WDM and HIF lead to opportunities for new plasma and target HEDP science

Near term (now through FY11)

1. **High density plasma neutralization of beams in high-field focusing solenoids (needed for 1 eV targets in FY09-FY10)**
2. **Short pulse injector for >0.1 μC bunch injection into NDCX-II**
3. **Time-dependent beam correction optics to reduce chromatic spot size, mitigate unwanted beam preheat, and enable multi-pulse (pump-probe) and /or beam pulse shaping.**
4. **Fast local diagnostics to measure beam deposition in optically thick targets.**
5. **Use hydro calculations to explore feasibility of asymmetric direct drive implosions with two-sided beam illumination with variable range ion beams.**

Medium term (FY12 through FY17), on NDCX-II and IB-HEDPX

1. **Develop understanding of two-phase isochoric heating and expansion.**
2. **Multi-pulse (pump-probe) beam hydrodynamics experiments.**
3. **Benchmark models for direct drive efficiency and stability experiments.**

Long range IFE vision: 20 year science campaign plan, funding needs, technical challenges, and an ultimate HIF vision

Indirect drive will remain an option for HIF while we plan to explore heavy ion driven direct drive.

• **NIF first ignition will be based on laser indirect drive, but later polar direct-drive ignition experiments are planned.**

•**The Robust Point Design study[1] was a self-consistent heavy ion accelerator and final focus/chamber design that met detailed 2-D heavy ion indirect drive target design requirements[2]**

•**NDCX-II provides an affordable opportunity to explore physics of heavy ion direct drive coupling that could motivate potentially higher gain direct drive HIF (John Perkins, work in progress).**

1) [S.S. Yu, et. Al.] Fus. Sci. & Tech. 44 (2003) 266]

2) [D.A. Callahan-Miller and M. Tabak, Phys. Plasmas, 7, 2083 (2000)]

The long-range HEDP/HIF science campaign envisions three levels

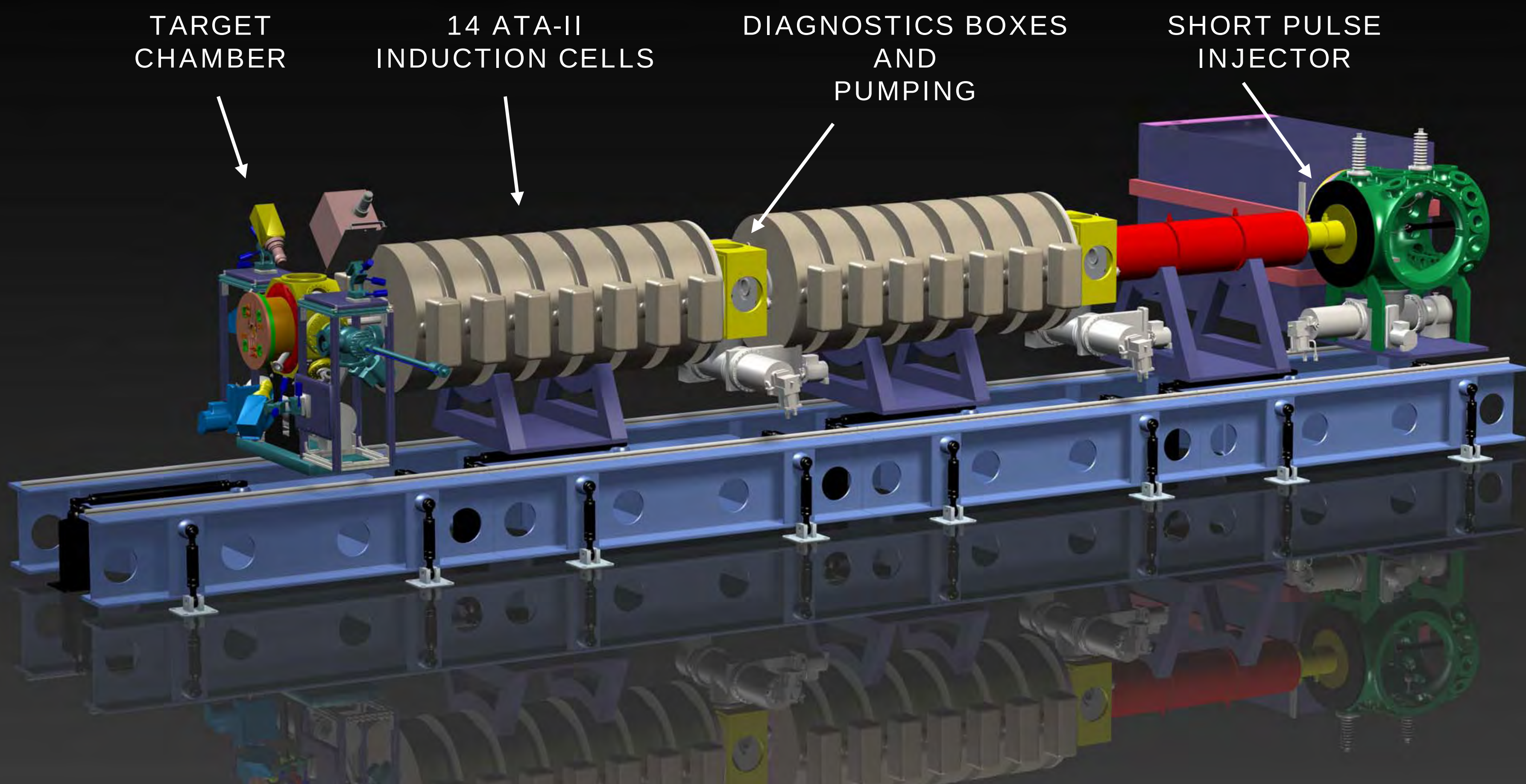
- **Level I (before NIF ignition to 2011)** **<u>Integrated beam-target physics:</u>** **Source-through-target physics models to be validated by experiments to predict target temperature profiles for WDM and direct drive physics @ 1 eV. *Best opportunity*: NDCX-II with existing ATA cells for 3-6 MeV beam with NDC and solenoid focus (single and double pulses) (~ 1.5 M hardware)**

- **Level II (In parallel with NIF operation ~2012-2025)** **<u>Ion direct drive implosion physics and 100 eV foam HEDP:</u>** **Explore heavy ion direct drive physics and HEDP at 100 eV. *Best opportunities*: NDCX-II, IB-HEDPX (~$50M), and a new 10 kJ beam tool for asymmetric direct drive implosion experiments (2 induction linacs @100 MeV w/ target chamber,~ $100M).**

- **Level III (Post NIF ~ 2025-2050?)** **<u>Heavy ion fusion physics:</u>** **Burning plasma physics with high pulse rate targets, fusion chamber materials and gas dynamics). *Best opportunity*: Fusion Test Facility (FTF) with HIF direct drive with gain >100 @ 1 MJ, for < $ 0.5 B. Target injection, T-breeding and liquid vortex chamber hydro validation at 3 Hz pulse rates.**

Campaign Level I can use existing equipment for both isochoric WDM physics and new double-pulse direct-drive experiments

Thanks to LLNL Beam Research Program, we have enough parts for 6 MeV of acceleration.
Our main cost item would be to replace solenoids to 1.5 to 2 T (6 m x 100K/m ~ $600K)



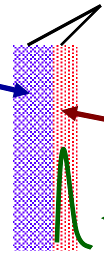
→NDCX-II: Validates CD-0 pre-requisite for IBX-HEDPX

SHOWN USING AVAILABLE ATA CELLS.
Blumlein pulsed power modules not shown.

Double-pulse planar target interaction experiments should reveal *unique* heavy-ion direct-drive coupling physics- *see Barnard's Wed. talk*

Solid D_2 "payload"

Time just before first pulse

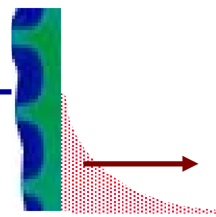


Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

Ablator D_2 layer ~ > than initial ion range

First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives

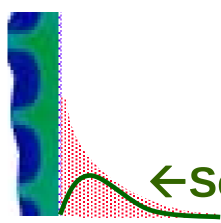


RT "bubbles & spikes" grow measurable amplitudes.

(1) Can upstream beam GHz RF modulation reduce RT?

(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

2nd higher energy ion pulse arrives, and stops ***partly within ablation blow-off*** (in 1-D)

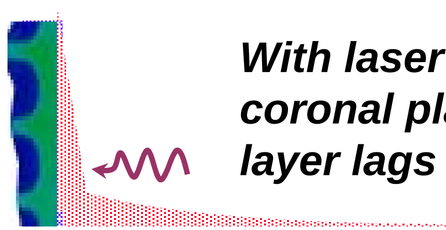


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses interacting with ablation layer mass?

←Second ns ion beam pulse dE/dx

(2) How is RT growth affected (any "cloudy day" effect?)

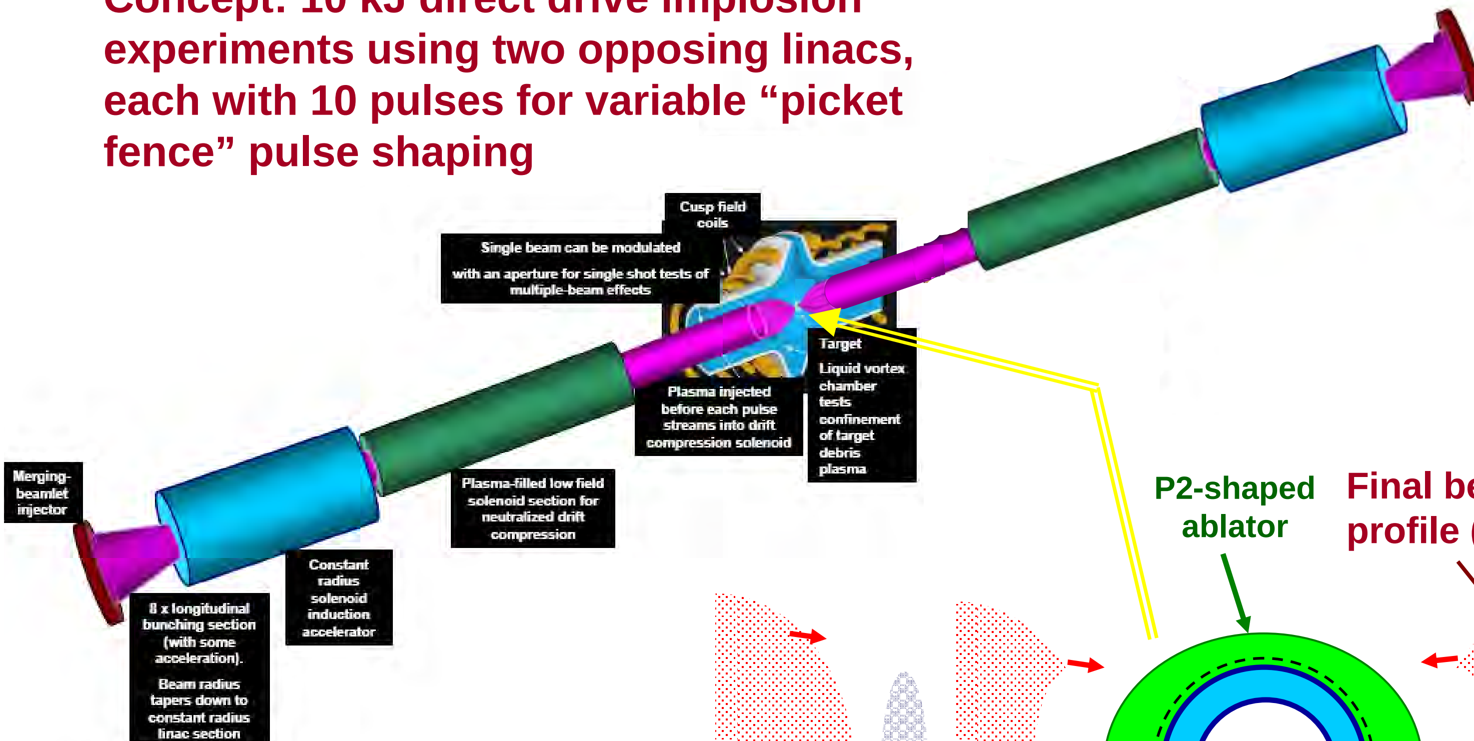
With laser direct drive, later pulse ablates at fresh critical density layer further left

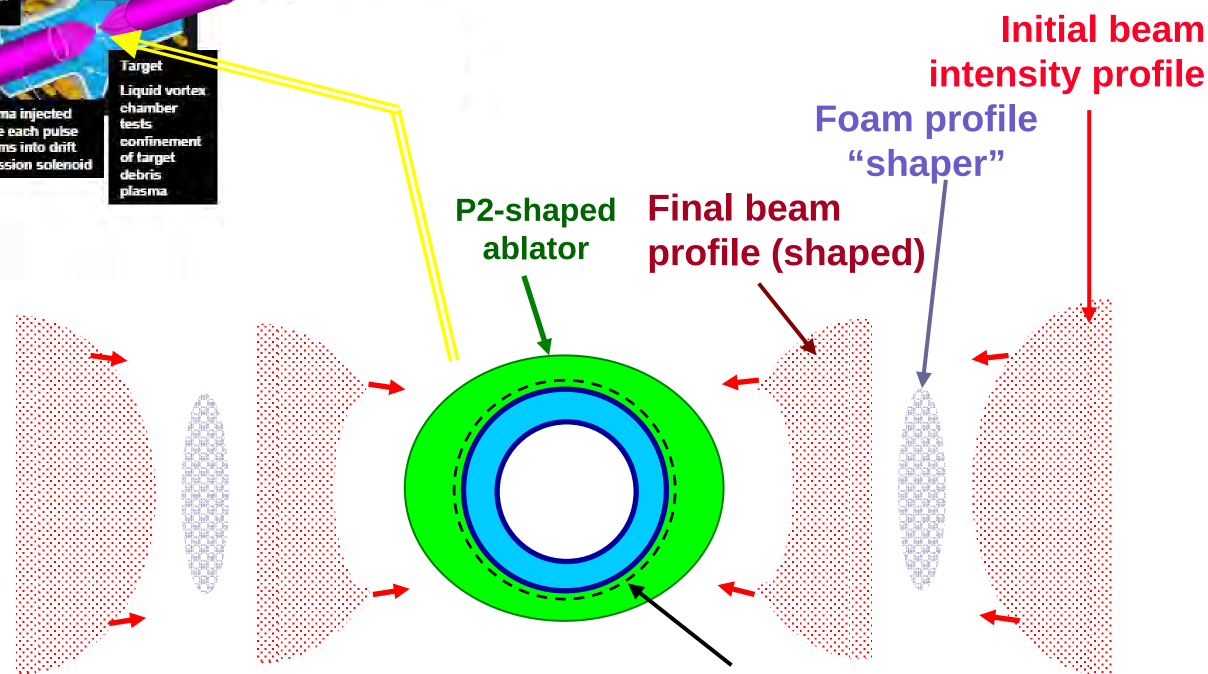


With laser direct drive, light transmits through most coronal plasma→ Absorption in inverse bremsstrahlung layer lags behind dense shell trajectory

Campaign Level II: In addition to IB-HEDPX, a new accelerator tool is needed to explore heavy-ion-driven fusion target physics and HEDP in parallel with NIF operation

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable "picket fence" pulse shaping





Three "knobs" to control P2 asymmetry with two beams:
1. Upstream GHz wobblers
2. Foam profile shapers
3. Ablator shaping

Goal is implosion drive pressure on the Cryo D_2 payload with < 1 % non-uniformity

Twenty-year science campaign and funding needs for heavy-ion-beam-driven HEDP and fusion research

Science Areas	FY06 FY07	FY08 FY09	FY10 FY11	FY12 FY13 FY14 FY15 FY16 FY17	FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25
Beam-Target Interactions	Target design + fast beam /target diagnostics	Beam dE/dx WDM exps.	Initial beam-cryo D2 target interaction	Operate IB-HEDPX WDM user facility: EOS, critical points, metal-insulator transitions for many materials	Operate IB-HEDPX WDM user facility: Physics of WDM phenomena relevant to NIF high yield and future FTF fusion chambers
Focusing onto Targets	Larger plasma source	Hi-B_{sol} focus w/ time dependent corrections	Double pulse target interaction	Ion planar direct drive hydro experiments with shaped double pulses	Optimize targets with pulse shaping in ion beam direct drive using ten-pulse bunch trains
Longitudinal Beam Compression	60x compression	60x compression with 20x focusing	Comp & focusing pulse-shaped ion bunches	Optimize compression and focusing using double pulse beams	Optimize compression and focusing using ten pulse bunch trains
High Brightness Beam Transport	E-cloud in: 4 quadrupoles 4 solenoids	Beam steering & brightness	Perp and par brightness in double pulses	Optimize beam perp & parallel brightness with double pulse beams	Optimize beam perp & parallel brightness with ten-pulse bunch beams
Advanced Theory and Simulations	Source to target models	Source through target models	Begin direct drive/ multi pulse models	Further develop and apply multi-pulse beam acceleration/ focusing models for both direct and indirect drive	Integrated accelerator beam with target hydro modeling
Facility & resource needs (Constant $ estimate)	1. Operate NDCX 2. Assemble NDCX-II $8M/yr tot	1. Operate NDCX I 2. Operate NDCX-II $10M/yr tot	1. Operate NDCX-I,II 2. Begin IB-HEDPX proj $16 M/yr tot	1. Complete and operate IB-HEDPX with support for Users ($20M/yr) 2. Construct heavy ion target implosion HEDP physics facility ($20M/yr) = $40M/yr tot.	1. Operate IB-HEDPX + Users ($20M/yr) 2. Operate heavy ion implosion physics facility (20M/yr) 3. HIF-IFE target & chamber R&D ($20M/yr) = $60 M/yr

First heavy ion WDM experiment @ < 1 eV

1 eV in targets; basis for IB-HEDPX

NIF Ignition Campaign

Potential implosion symmetry tests in NIF of four successive no-yield capsules on the fly to understand precision requirements for IFE (suggested, not included in this budget)

20yr Objective: Develop the beam and target physics knowledge base for a heavy-ion fusion test facility

Selected major technical challenges to improve heavy ion fusion

<u>Long term (FY17-FY25)</u>

Specific to reduce heavy-ion fusion driver cost:

1. **Beam 6-D phase space density after acceleration sufficient to focus to required target spot sizes and pulse widths at high line-charge densities (10-30 μC/m).**
2. **Control of e-cloud effects in vacuum transport regions of the accelerator.**
3. **Improve overall coupling efficiency (beam to imploded fuel energy) from 2 % to perhaps 20% (e.g., with direct drive)**

Generic to several IFE approaches including HIF:

1. **Demonstrate precision injection, tracking *<u>and implosion symmetry</u>* in multi-shot, on-the-fly, no-yield target experiments (*before* any high average power ETF).**
2. **Develop relevant-hydro-scale thick liquid protected chambers compatible with required target insertion repetition rate.**
3. **Develop low cost injectable targets for (1) scalable to IFE cost goal~<25cts.**

Conclusion

- We have developed a 20 year plan for HEDP physics driven by heavy ion beams that is relevant to inertial fusion energy and which leverages significant current experimental equipment and the National Ignition Facility.
- NDCX-I is a current productive test bed for new beam compression and focusing methods, and for diagnostics for warm dense matter experiments which begin next year. Theory and simulations support every aspect of our experimental program.
- We have sufficient ATA accelerator modules to build NDCX-II, requiring only a small $ 1.5 M hardware investment.
- NDCX-II is the key next step to begin learning heavy-ion beam target physics. Along with NIF, NDCX-II can provide the basis for a 10 kJ scale heavy ion implosion facility to enable an attractive direct drive heavy-ion fusion concept.
- This program may lead to a unique vision for HIF with direct conversion and self-T-breeding targets.

Z-IFE (Z-Pinch Inertial Fusion Energy)

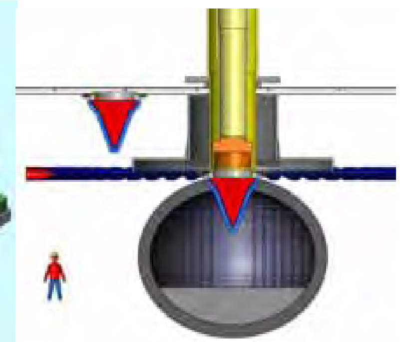
Z-IFE Results
Current Status and Near-Term Plans
Long-Range Vision
Funding needs to move to the next step

RTL

LTD driver

Shock Mitigation

Z-PoP



Chamber

Craig L. Olson
Z-IFE Program Manager

IFE Science & Technology Strategic Planning Workshop
Marriott Hotel
San Ramon, California
April 24-27, 2007

The Z-Pinch IFE Team (FY06)

C. Olson 1), G. Rochau 1), M. Mazarakis 1), K. Struve 1), M. Savage 1), D. Smith 1), T. Pointon 1), D. Seidel 1), M. Kiefer 1), S. Rosenthal 1), K. Cochrane 1), L. Chhabildas 1), J. Lawrence 1), R. McKee 1), L. Shipers 1), F. Long 1), J. Jones 1), J. McDonald 1), P. Wakeland 1), R. Olson 1), M. Cuneo 1), W. Stygar 1), S. Slutz 1), R. Vesey 1), T. Mehlhorn 1), B. Cipiti 1), J. Cook 1), C. Morrow 1), S. Rodriguez 1), C. Farnum 1), M. Modesto 1), D. Oscar 1), V. Vigil 1), R. Keith 1), M. Turgeon 1), E. Lindgren 1), S. Durbin 1), H. Tran 1), A. Guild-Bingham 1), W. Martin 1), M. Pelock 1), C. Walker 1), J. Romero 1), D. McDaniel 1), J. Quintenz 1), M. K. Matzen 1), J. P. VanDevender 1), W. Gauster 1), L. Shephard 1), M. Walck 1), T. Renk 1), T. Tanaka 1), M. Ulrickson 1), W. Meier 2), J. Latkowski 2), R. Moir 2), S. Reyes 2), R. Abbott 2), D. Callahan 2), R. Peterson 3), J. Grondalski 3), P. Ottinger 4), J. Schumer 4), P. Peterson 5), C. Debonnel 5), D. Kammer 6), G. Kulcinski 6), L. El-Guebaly 6), G. Moses 6), T. Heltmes 6), E. Marriott 6), P. Wilson 6), I. Sviatoslavsky 6), G. Sviatoslavsky 6), M. Sawan 6), M. Anderson 6), R. Bonazza 6), J. Oakley 6), J. De Groot 7), N. Jensen 7), M. Abdou 8), A. Ying 8), P. Calderoni 8), L. Schmitz 8), S. Abdel-Khalik 9), C. Lascar 9), D. Sadowski 9), M. Barkey 10), R. Gallix 11), C. Charman 11), H. Shatoff 11), P. Mijatovic 11), D. Welch 12), D. Rose 12), N. Bruner 12), T. Genoni 12), B. Oliver 12), P. Panchuk 13), S. Dean 14), A. Kim 15), Yu. Kalinin 16), G. Shatalov 16), S. Nedoseev 16), E. Grabovsky 16), A. Kingsep 16), V. Smirnov 16)

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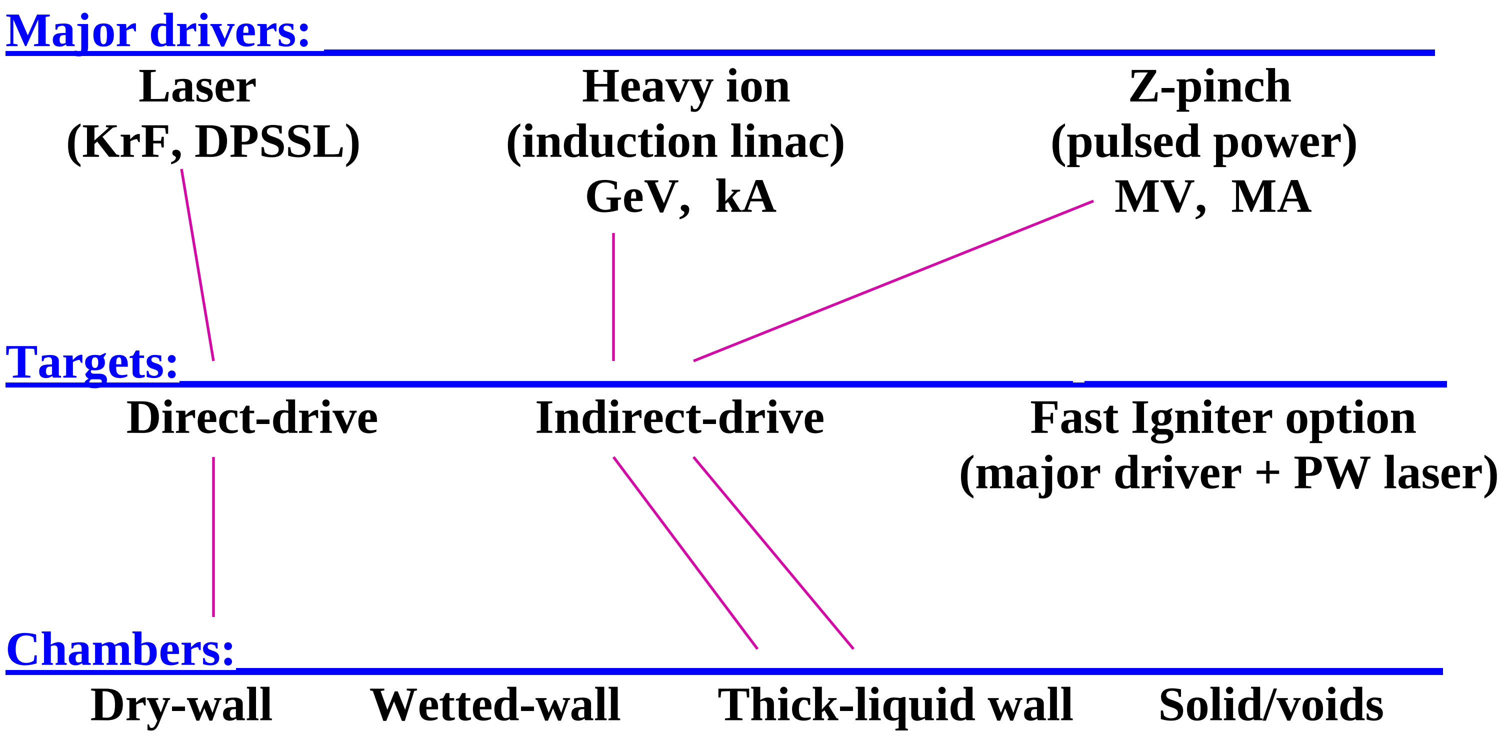
15) Institute of High Current Electronics, Tomsk, Russia
16) Kurchatov Institute, Moscow, Russia

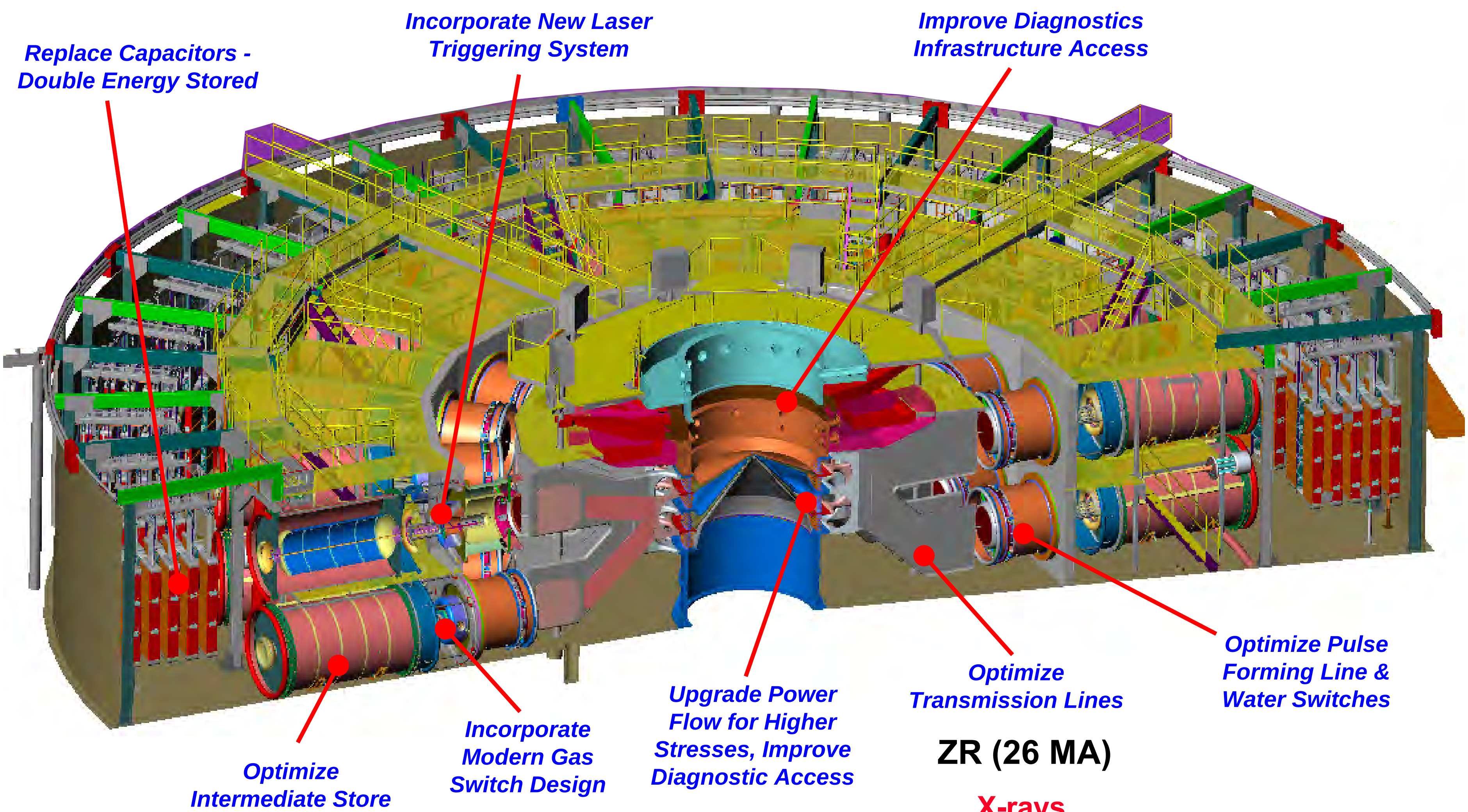
Z-Pinch is the newest of the three major drivers for IFE

1999 Snowmass Fusion Summer Study, IAEA CRP on IFE Power Plants,
2002 Snowmass Fusion Summer Study, FESAC 35-year plan Panel Report (2003),
FESAC IFE Panel Report (2003)



Thick liquid walls essentially eliminate the "first wall" problem, and lead to a faster development path: no new neutron test facilities required

ZR - Refurbishing the Entire Accelerator



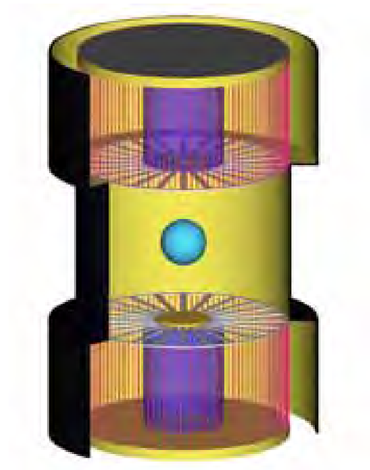
ZR (26 MA)

X-rays
~2.7 MJ
~350 TW

Sandia National Laboratories

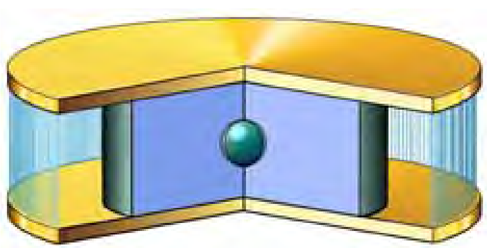
Simulation results and scaling of Z-pinch indirect-drive target concepts for high-yield ICF and Z-IFE

Double-Ended Hohlraum



	ICF → IFE
Peak current	2 x (62 – 116) MA
Energy delivered to pinches	2 x (19 – 67) MJ
Z-pinch x-ray energy output	2 x (9 – 33) MJ
Capsule absorbed energy	1.2 – 8.6 MJ
Capsule yield	400 – 4500 MJ
	G~11 *G~34*

Dynamic Hohlraum



Peak current	56 – 95 MA
Energy delivered to pinch	14 – 42 MJ
Capsule absorbed energy	2.4 – 7.2 MJ
Capsule yield	530 – 4600 MJ
	G~38 *G~110*

J. Hammer, M. Tabak (LLNL)   J. Lash, S. Slutz, R. Vesey, W. Stygar

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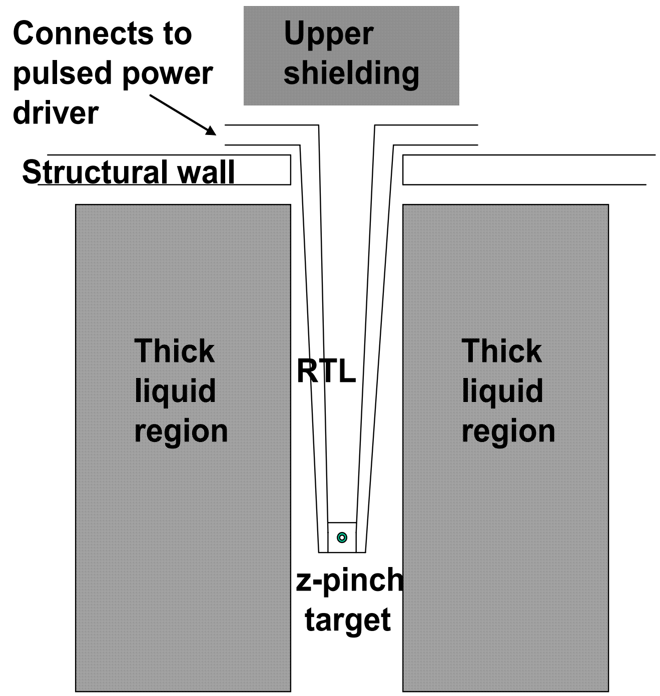
Recyclable Transmission Line (RTL) Concept for Z-Pinch IFE



Yield and Rep-Rate: few GJ every 3-10 seconds per chamber (0.1 Hz - 0.3 Hz)
Thick liquid wall chamber: only one opening (at top) for driver; nominal pressure (10-20 Torr)
RTL entrance hole is only 1% of the chamber surface area (for R = 5 m, r = 1 m)
Flibe absorbs neutron energy, breeds tritium, shields structural wall from neutrons
Neutronics studies indicate 40 year wall lifetimes
Activation studies indicate 1-1.5 days cool-down time for RTLs
Studies of waste steam analysis, RTL manufacturing, heat cycle, etc. in progress

- Eliminates problems of final optic, pointing and tracking N beams, and high-speed target injection
- Requires development of RTL

Sandia National Laboratories

Z-Pinch IFE Power Plant has a Matrix of Possibilities

Repetitive Z-Pinch Driver:

Marx generator/ water line technology

magnetic switching (RHEPP technology)

linear transformer driver (LTD technology)

RTL (Recyclable Transmission Line):

frozen coolant (e.g., Flibe/ electrical coating)

immiscible material (e. g., carbon steel)

Target:

double-pinch

dynamic hohlraum

advanced targets

fast ignition

Chamber:

dry-wall

wetted-wall

thick-liquid wall

solid/voids (e. g., Flibe foam)

Recent Results in Z-IFE

1. RTLs

   simulations (> 5 MA/cm works)

   experiments (> 5 MA/cm works)

   fabrication of PoP-size RTLs
   and pressure testing

2. LTD repetitive driver

   0.5 MA, 100 kV LTD cavity
   fires every 10 seconds

   1.0 MA, 100 kV LTD cavities (5)
   voltage-adder tests

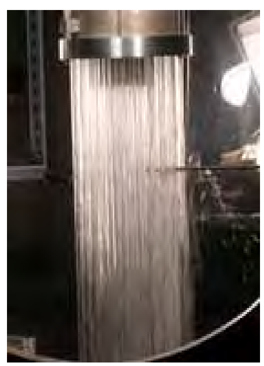
   full IFE driver architectures

3. Shock mitigation

   theory

   experiments: water ring/explosives
   foamed liquids
   shock tube/foams

   simulations



4. Z-PoP planning

   vacuum/electrical
   connections
   overhead automation
   animations

   costing

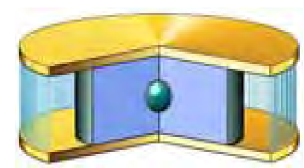
5. Z-IFE targets for 3 GJ yields

   gains ~ 50-100

   double-pinch/dynamic hohlraum

   advanced targets

   scaling studies

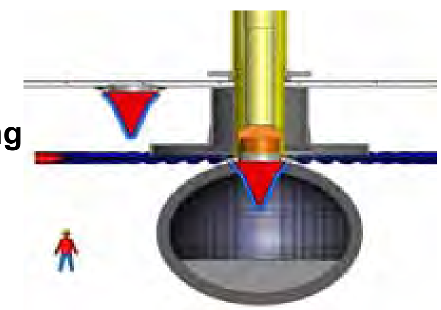


6. Z-IFE power Plant

   RTL manufacturing/costing

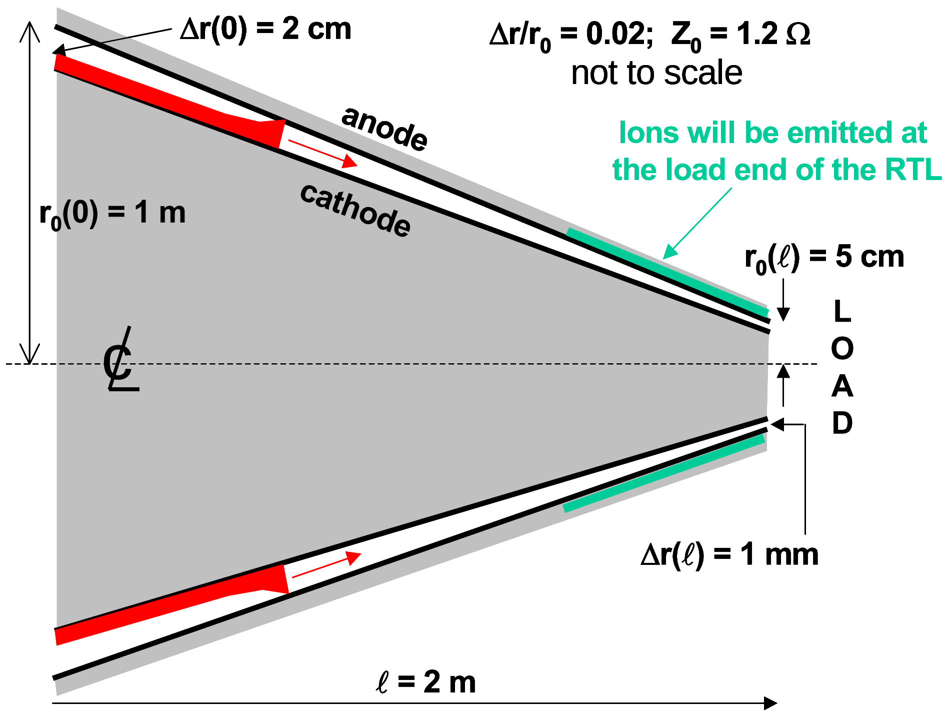
   wall activation studies:
   40 year lifetime

   power plant design
   +GNEP, transmutation

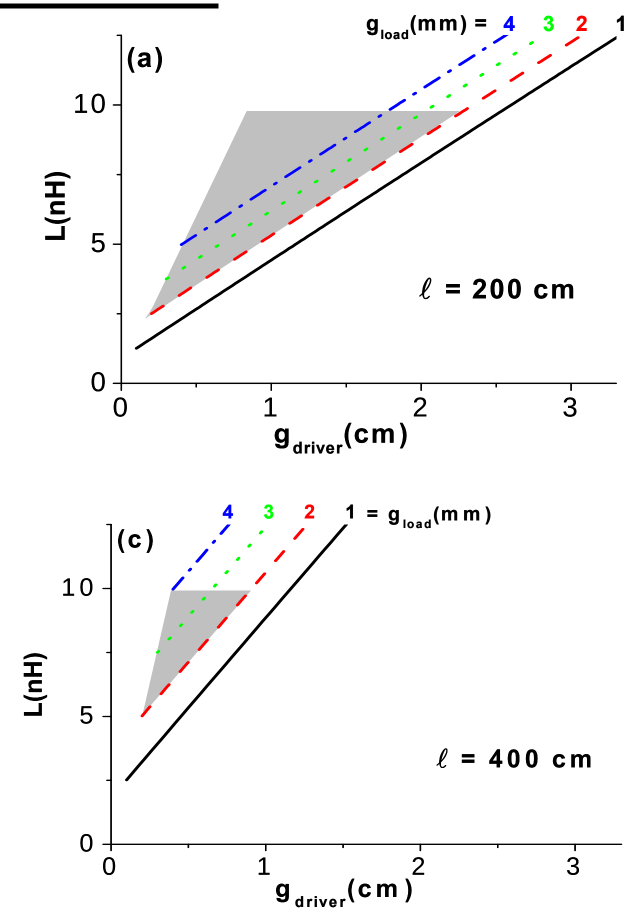


Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The physics of electron and ion flow in RTLs has been studied analytically and with LSP simulations: AK gaps at the load should be $\geq$ 2 mm



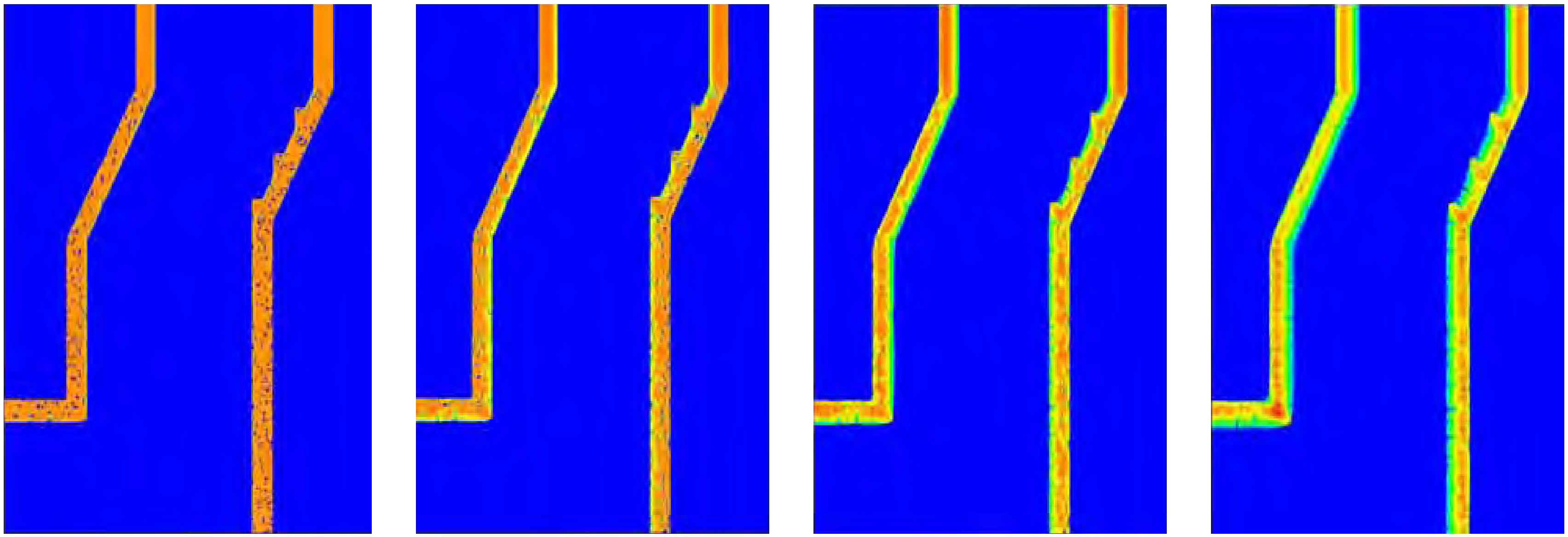
Conical tapered RTL for the baseline Z-IFE design. Power is fed in from the left.



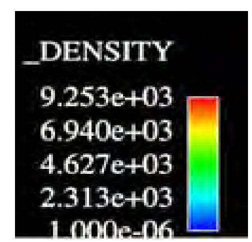
RTL inductance as a function of AK gap at the input end for various values of AK gap at the load. Shaded area are allowed design areas.

P. Ottinger, J. Schumer (NRL)

ALEGRA simulations of RTL with random imperfections still shows robust power flow



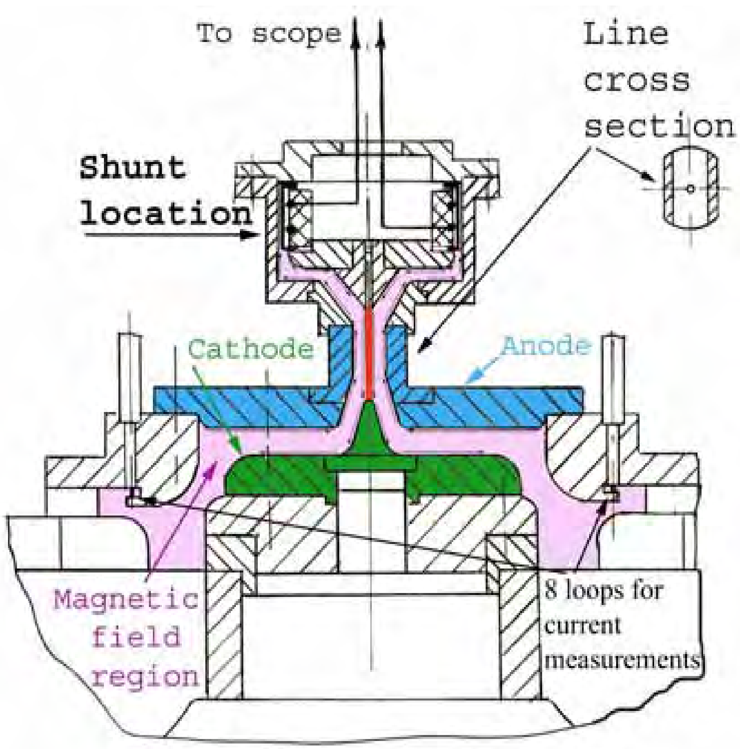
t = 15 ns 30 ns 45 ns 60 ns



AK gap: 2 mm
RTL wall thickness: 0.025 inches = 635 microns
Power pulse: rising to 60 MA in 100 ns

S. Rosenthal, K. Cochrane (SNL)

Experiments and simulations at Kurchatov show plasma formation does not result in gap closure at 6 MA/cm.



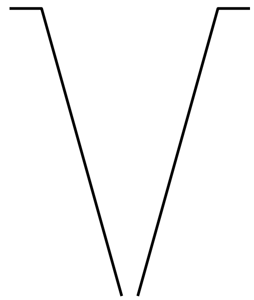
Experiment on S-300 at Kurchatov Institute, Moscow, Russia

The series of experiments has been carried out aimed at the investigation of the MITL section at the linear current densities up to 6 MA/cm that is typical of the Pulsed Power Fusion Energy plant. The temporal behavior of both input and output current in the MITL section is identical up to 220-260 ns. At this stage, it has been found that the plasma formed as a result of electrodes surface explosion, did not reconnect the MITL gap. The process of electrodes explosion and subsequent dense plasma dynamics fairly corresponds to the predictions of numerical simulations based on the 1-D MHD NPINCH code taking into account EOS for metals and plasmas.

V. Smirnov, A. Kingsep, et al. (Kurchatov, Moscow)

RTL sizes

Power Plant



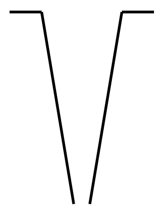
R = 100 cm

L = 200 – 500 cm

r = 5 cm

Test RTLs

Fabricated and pressure tested



R = 50 cm

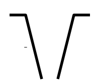
L = 200 cm

r = 5 cm

thickness: 0.025 inches (635 microns)

Z-PoP

Fabricated and pressure tested



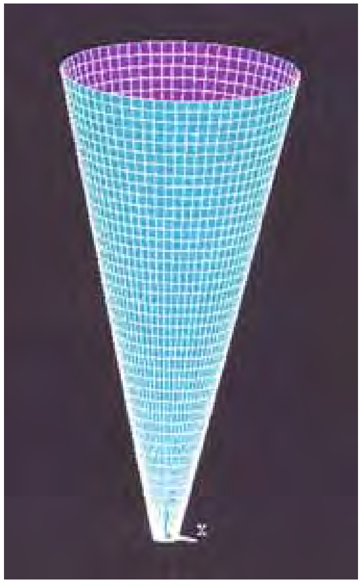
R = 16 cm

L = 64 cm

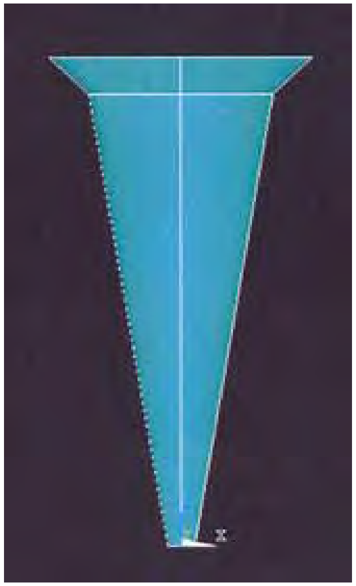
r = 2-5 cm

(For 10 module Z-Pop, with10 MA, gives 0.1 MA/cm at clamp – same as for 60 MA with R = 100 cm)

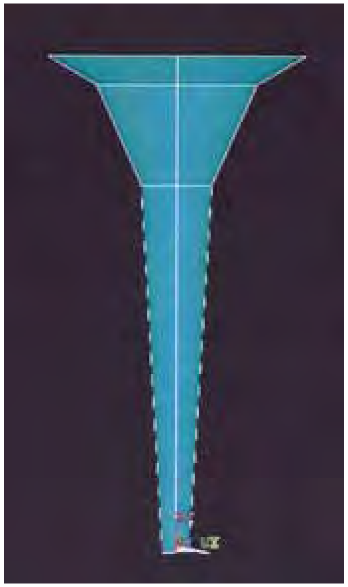
RTL buckling mode analysis leads to optimized RTL shape, that permits lower mass RTLs



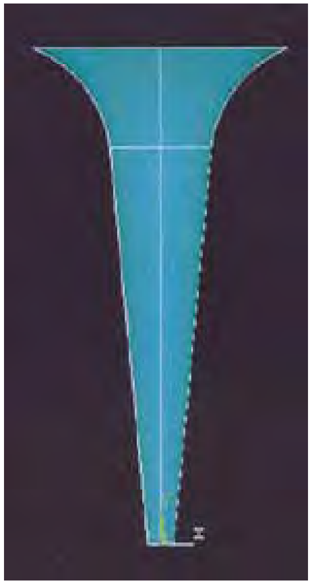
Single segment RTL



Two-segment RTL



Three-segment RTL



Curved RTL

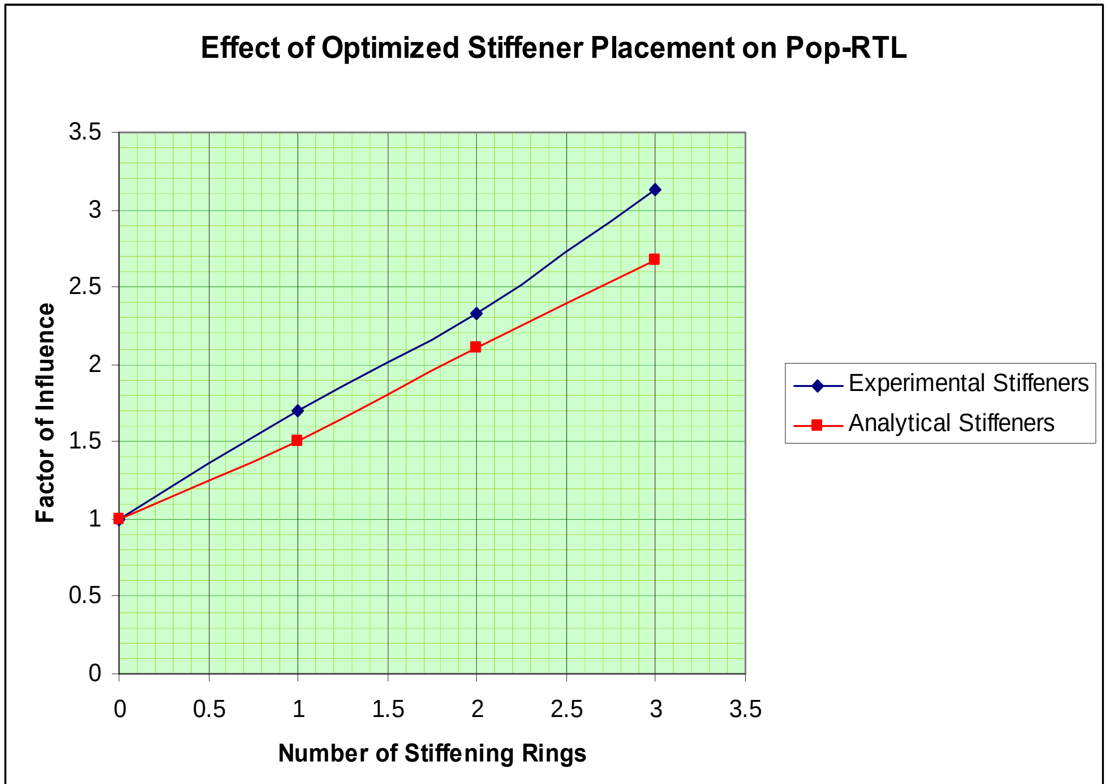
RTL design	Eigenbuckling Pressure (dyne/cm^3)	Enhancement over single-segment
single-segment	249,755	1.0
two-segment	490,117	1.96
three-segment	730,507	2.92
curved	748,966	3.00

D. Kammer, B. Wilson (University of Wisconsin)

(22) PoP-RTLs were constructed and pressure tested to buckling with various stiffening rings

PoP-RTL cone made by Toledo Metal Spinning

Stiffening rings mounted to PoP- RTL cone

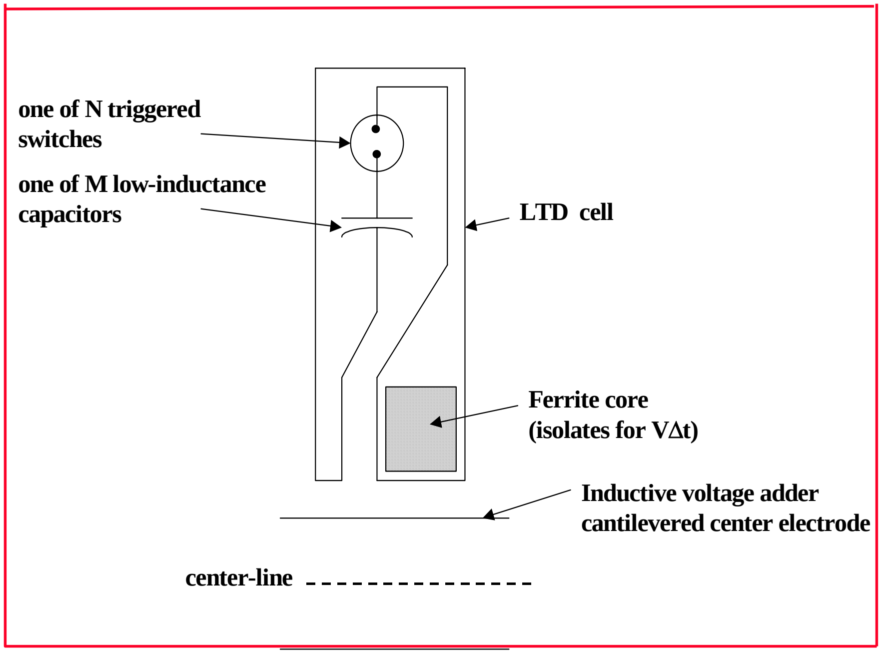


Stiffeners significantly increase the structural performance of the PoP-RTL without adding significant mass

M. Turgeon (SNL), M. Barkey (U. Alabama)

Linear Transformer Driver (LTD) technology is compact and easily rep-rateable

- LTD uses parallel-charged capacitors in a cylindrical geometry, with close multiple triggered switches, to directly drive inductive gaps for an inductive voltage adder driver (Hermes III is a 20 MV inductive voltage adder accelerator at SNL)
- LTD requires no oil tanks or water tanks
- LTD accelerator volume about 1/4 -1/3 the volume of Marx/water line technology (as used in Saturn and Z)
- LTD pioneered at Institute of High Current Electronics in Tomsk, Russia



Modular

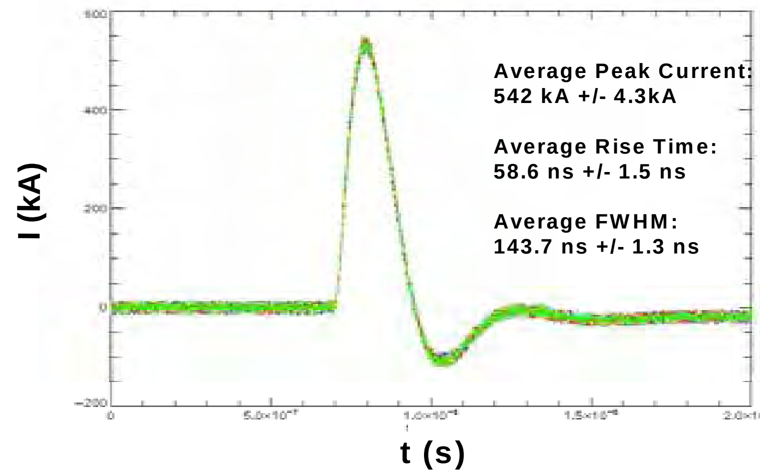
High Efficiency

Low Cost (estimates are ~1/2 that for Marx/water line technology)

Easily made repetitive for 0.1 Hz

Repetitive, 0.5 MA, 100-kV LTD Cavity is in operation at SNL

SNL high current LTD Laboratory



Overlay of 100 shots at 0.03 Hz
for 90 kV charging

40 Maxwell 31165 caps,
20 switches, ±100 kV
0.2 Ohm load 0.05TW

At SNL: This 0.5 MA cavity has been fired in repetitive mode for ~3000 shots; the last set of 50 shots with one shot every 10.25 seconds (~0.1 Hz)

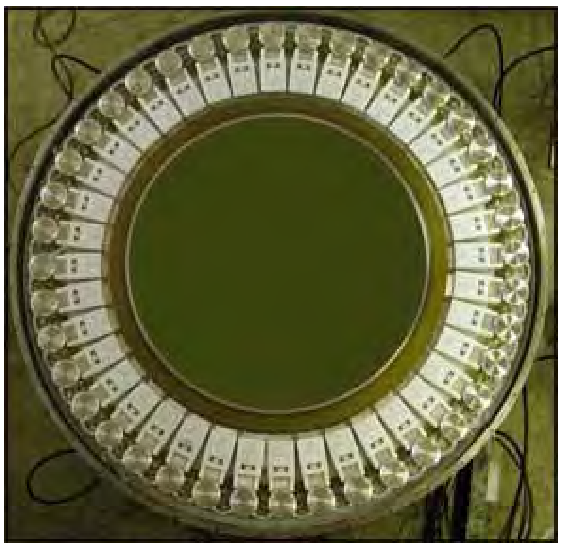
At Tomsk: One switch has been fired 37,000 shots with one shot every 12 seconds (~0.08 Hz)

M. Mazarakis, W. Fowler, R. Sharpe (SNL) A. Kim (HCEI, Tomsk)

Sandia National Laboratories

Five 1.0 MA LTD cavities have been built in Tomsk, Russia (this is the building block for Z-PoP and future Z-IFE drivers)

3-m



1-MA, 100kV, 70ns LTD cavity
(top flange removed)

80 Maxwell 31165 caps,
40 switches, ±100 kV
0.1 Ohm load 0.1TW

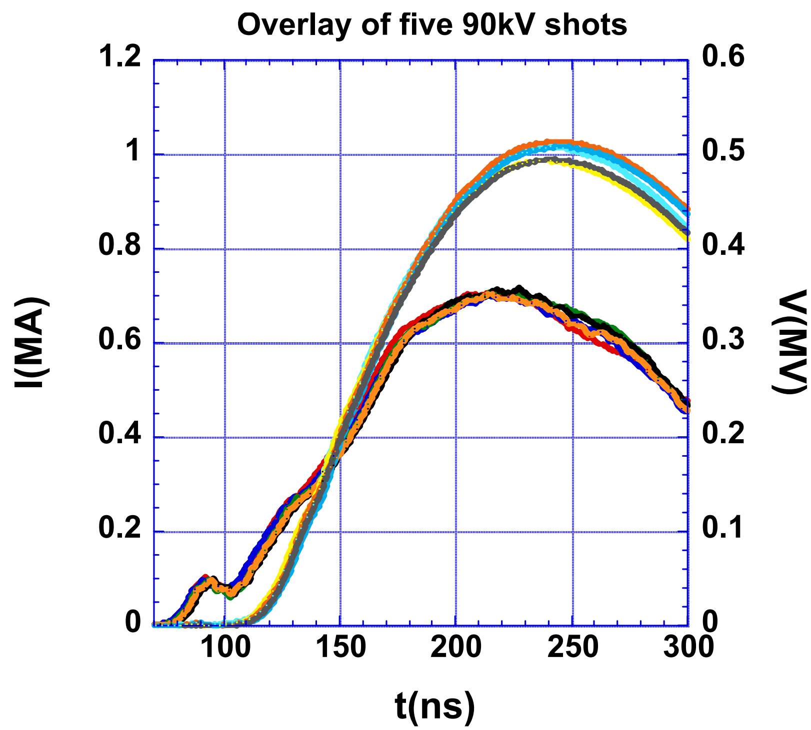
Test stand for Voltage adder testing of five 1.0 MA LTD cavities (High Current Electonics Institute – Tomsk, Russia)

September 2006

M. Mazarakis, et al. (SNL) A. Kim, et al. (HCEI, Tomsk)

Sandia National Laboratories

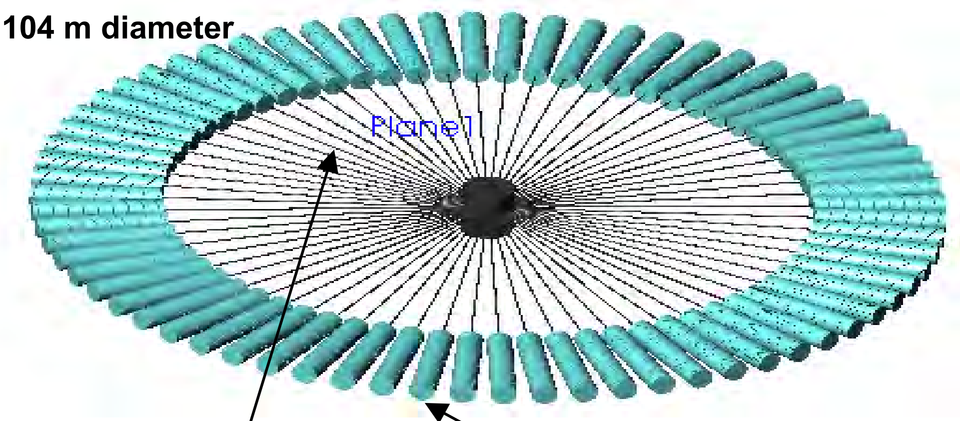
Five 1 MA LTD cavities were tested in a voltage-adder configuration at HCEI, Tomsk



M. Mazarakis, et al. (SNL)   A. Kim, et al. (HCEI, Tomsk)

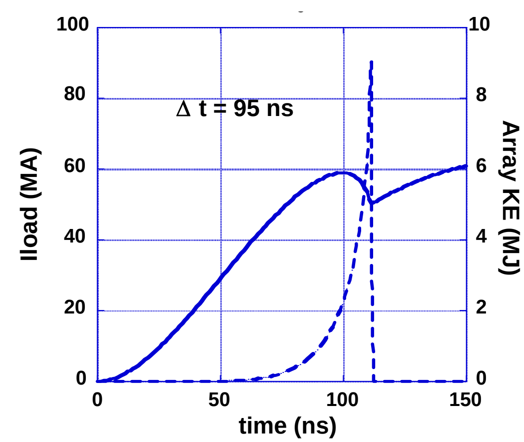
An IFE driver (60 MA), with seventy 1-MA voltage-adder modules, each with 70 LTD cavities (SNL)

104 m diameter

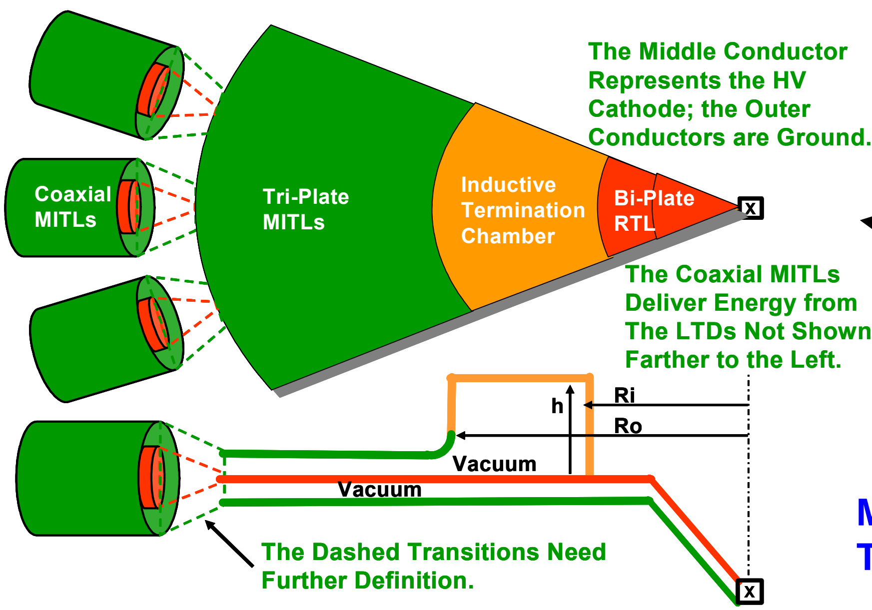


Coaxial MITL

1 MA voltage adder module



55 mg array load



Top pie-section and side views of the Coaxial to Tri-Plate to Bi-Plate transition geometry

M. Mazarakis, D. Smith,
T. Pointon, W. Langston (SNL)

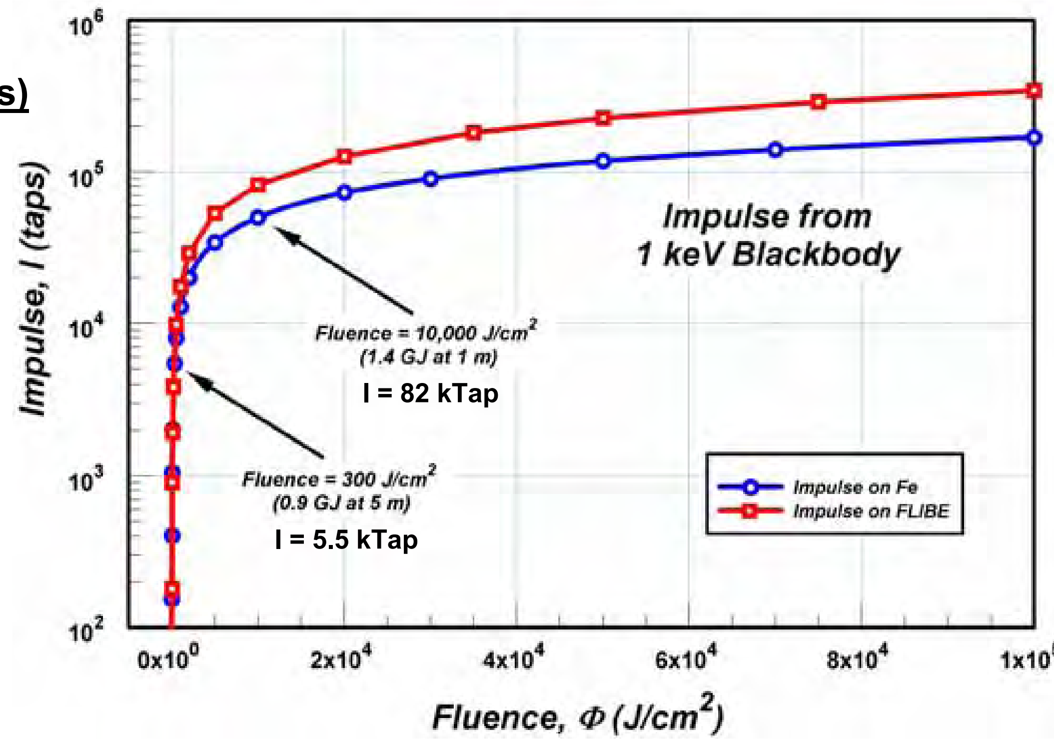
Sandia National Laboratories

Shock mitigation methods are being investigated to reduce the x-ray shock impulse on the thick liquid wall before it reaches the structural wall

<u>Example: 3 GJ yield (0.9 GJ in x-rays)</u>

<u>Flibe at 1 m radius:</u>
X-ray fluence is 7 kJ/cm²
Peak pressure is 45 Mbar
Impulse is 34 kTap

<u>Flibe at 5 m radius:</u>
X-ray fluence is 300 J/cm²
Peak pressure is 1.8 Mbar
Impulse is 1.4 kTap



<u>Typical Lethality Response Levels:</u>

- Light-weight structure (*e.g.*, satellite)
  - > 1 to 10 ktaps *
- Medium-weight structure (*e.g.*, airframe)
  - > 10 to 30 ktaps
- Robust structure (*e.g.*, RV)
  - > 30 to 80 ktaps

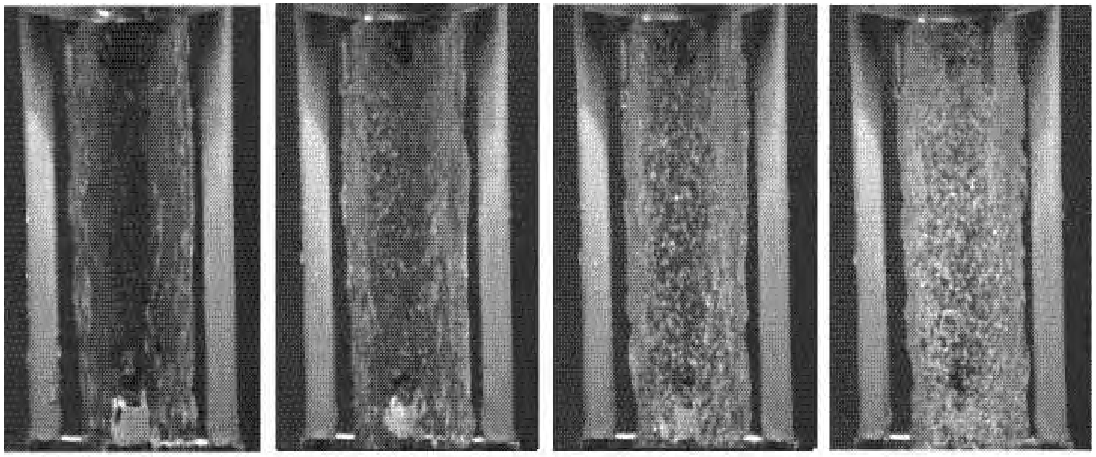
(1 kTap = 100 Pa s = 1 Mbar ns)

Impulse needs to be reduced by a small factor (1.5 or more) before it reaches the structural wall

J. Lawrence, L. Chabildas (SNL)

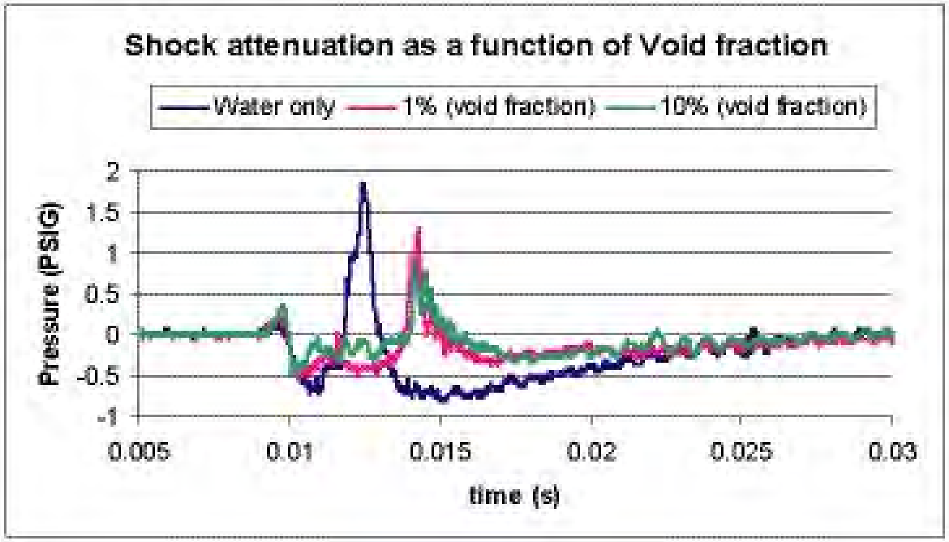
Sandia National Laboratories

Annular water jets with an exploding wire on axis are used to study shock mitigation for thick liquid walls



0% 1% 5% 10%

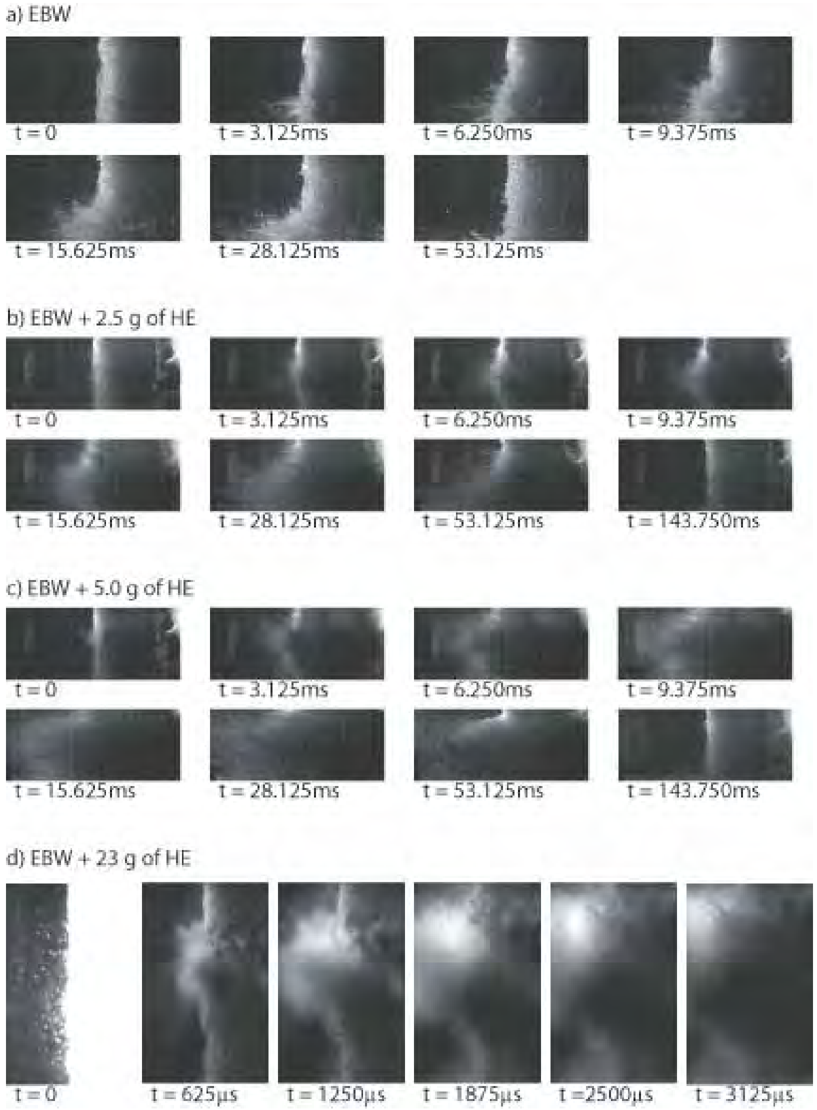
Photographs showing near-field behavior of two-phase annular jets with different void fractions (liquid superficial velocity v = 2 m/s)



Shock impulse attenuated by factor of 1.4

S. Abdel-Khalik, et al. (Georgia-Tech)

Annular water jet + high explosives used to investigate shock mitigation for thick liquid walls (VHEX facility)



Exploding bridge wire (EBW)
Peak pressure: 4.5 atmospheres
Impulse duration: 180 μs
Raw integrated impulse: 22 Pa.s

EBW + 2.5 g of HE (C4)
Peak pressue: 21 atmospheres
Impulse duration: 140 μs
Raw integrated impulse: 55 Pa.s

EBW + 5 g of HE (C4)
Peak pressure: 105 atmospheres
Impulse duration: 80 μs
Raw integrated impulse: 100 Pa.s

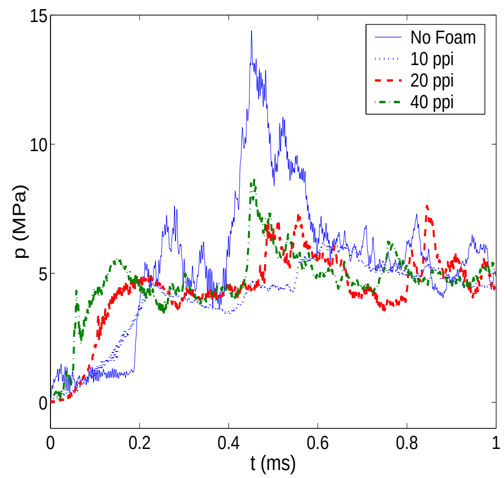
EBW + 23 g of HE (C4)

Crushing of porous liquid structures transfers momentum uniformly into the blanket mass without jetting or spall

P. Peterson, et al., UCB

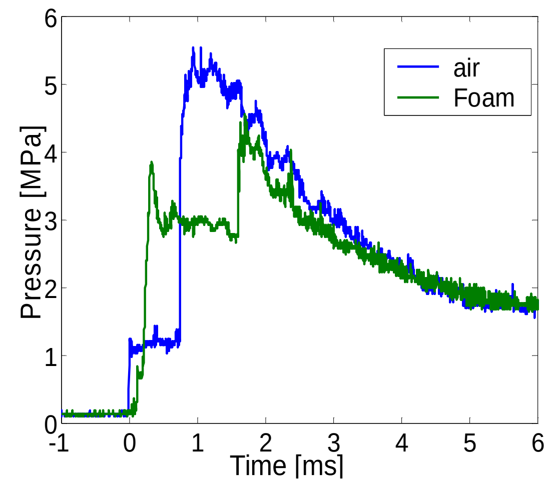
Shock Mitigation is studied with metallic foams and two-phase liquids at the shock tube facility at U. Wisconsin

Open cell morpholgy for <u>Al foams</u> as a function of pore size; (a) 10 ppi, (b) 20 ppi, (c) 40 ppi



Pressure traces from transducer located 3.81 cm above endwall for <u>Al foams</u>

Impulse was reduced 25%, 19.5%, 14% for 10, 20, 40 ppi solid foams



Pressure traces from a transducer located 1 m below the surface of a <u>very low density liquid foam.</u>

Impulse was reduced 22%.

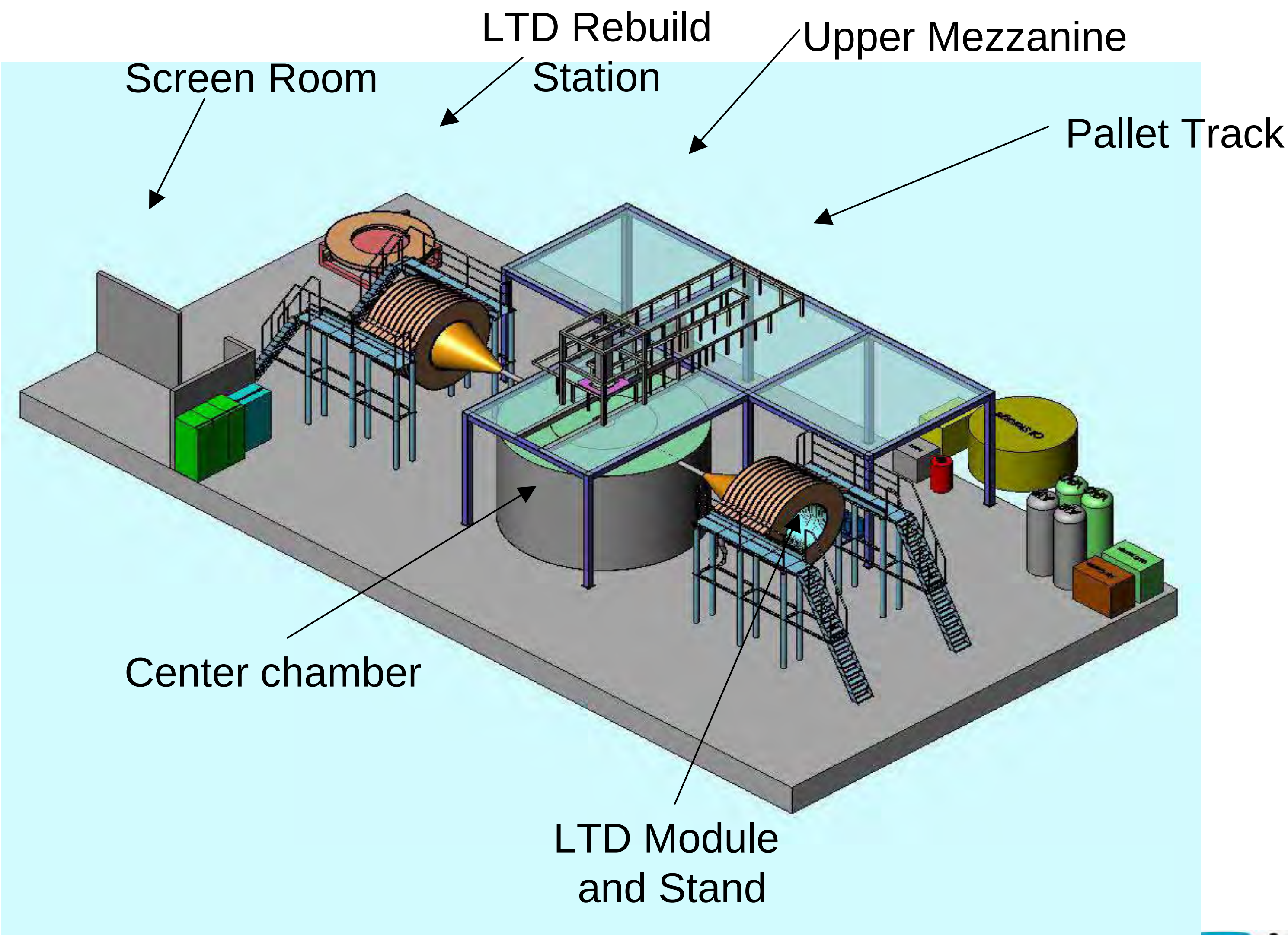
G. Kulcinski, M. Anderson, et al. (U. Wisconsin)

Z-PoP

- Z-PoP (Proof-of-Principle) is an experiment designed to demonstrate proof-of-principle of the repetitive pulsed power operations necessary for a pulsed power driven IFE power plant.
- Z-PoP will consist of a Linear Transformer Driver (LTD) pulsed power driver, connected to a Recyclable Transmission Line (RTL), which in turn is connected to a Z-pinch load.
- After each shot, an automated system will remove the RTL/z-pinch load and replace it with a new RTL/Z-pinch load.
- The sequence will repeat at about 0.1 Hz (i.e., every 10 seconds), the same as envisioned for an IFE power plant
- Z-PoP will be the first demonstration of a repetitive high current z-pinch, as would be used in an IFE power plant.

R. McKee, Larry Shipers, Finis Long, James Jones,
Jeff McDonald, Pete Wakeland (SNL)

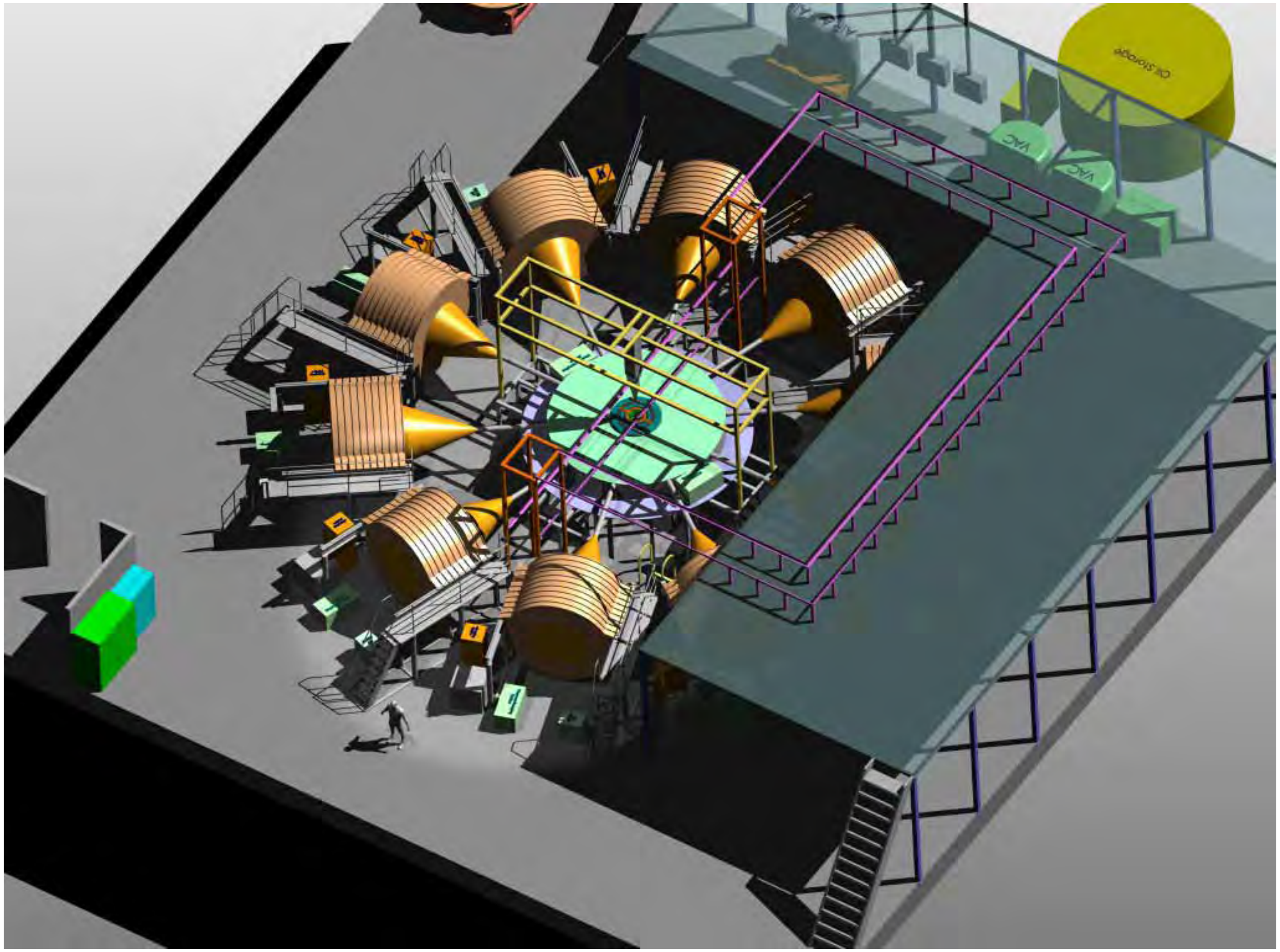
Z – PoP (two 1 MA legs)



Cost Estimate: two lines in three years: $15 M in FY05 $

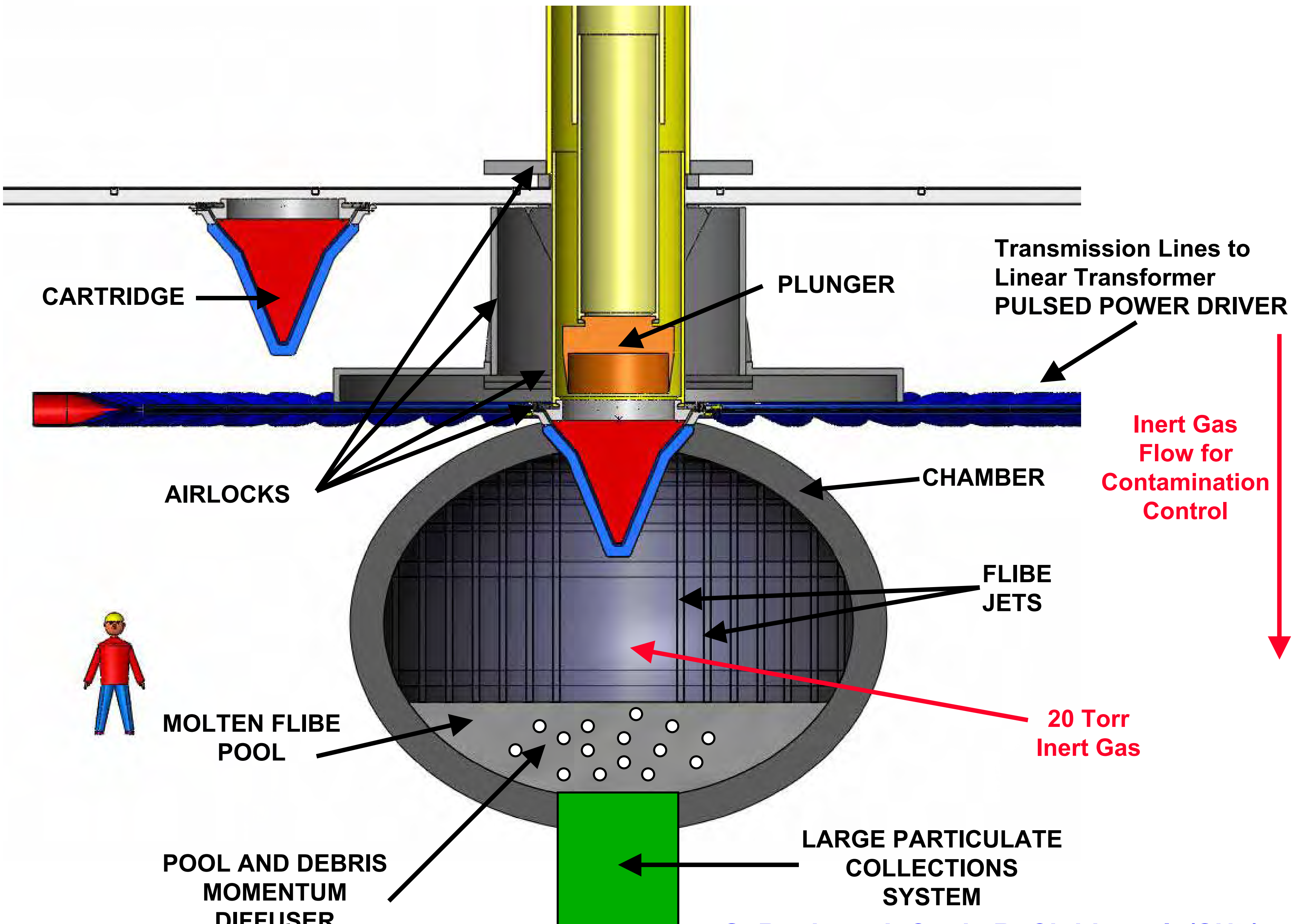
Z – PoP (ten 1 MA legs)

comparable to a rep-rated Saturn at 10 MA



Cost Estimate: ten lines in five years: $35.2 M in FY05 $

BASE Z-IFE Power Plant UNIT



G. Rochau, J. Cook, B. Cipiti, et al. (SNL)

Z-Pinch Power Plant Baseline Parameters

Target Yield	3 GJ
Rep. Rate (per chamber)	0.1 Hz
Fusion Power per chamber	300 MWth
Number of Chambers	10

Chamber

Shape	Spherical or Ellipsoidal
Dimension	4 m internal radius
Material	F82H Steel
Wall Thickness	15-30 cm

Coolant

Coolant Choice	Flibe
Jet Design	Circular Array
Standoff (Target to First Jet)	0-2 m
Void Fraction	0.05 – 0.67
Curtain Operating Temperature	950 K
Average Curtain Coolant Flow	12 m^3/s
Heat Exchanger Coolant Flow	0.47 m^3/s
Heat Exchanger Temp. Drop	133 K
Pumping Power	1.3 MW/chamber
Heat Cycle	Rankine
Heat Exchanger Type	Shell and Tube

Tritium Recovery

Breeding Ratio	1.1
Tritium Recovered per Shot	0.017 g
Extraction Type	Countercurrent

RTL

RTL Material	1004 Carbon Steel
Cone Dimensions	1 m Ø x 0.1 m Ø x 2 m h
Outer Cone Thickness	0.9 mm → 0.52 mm
Inner Cone Thickness	0.52 mm
Mass per RTL (2 cones)	50 kg → 34 kg

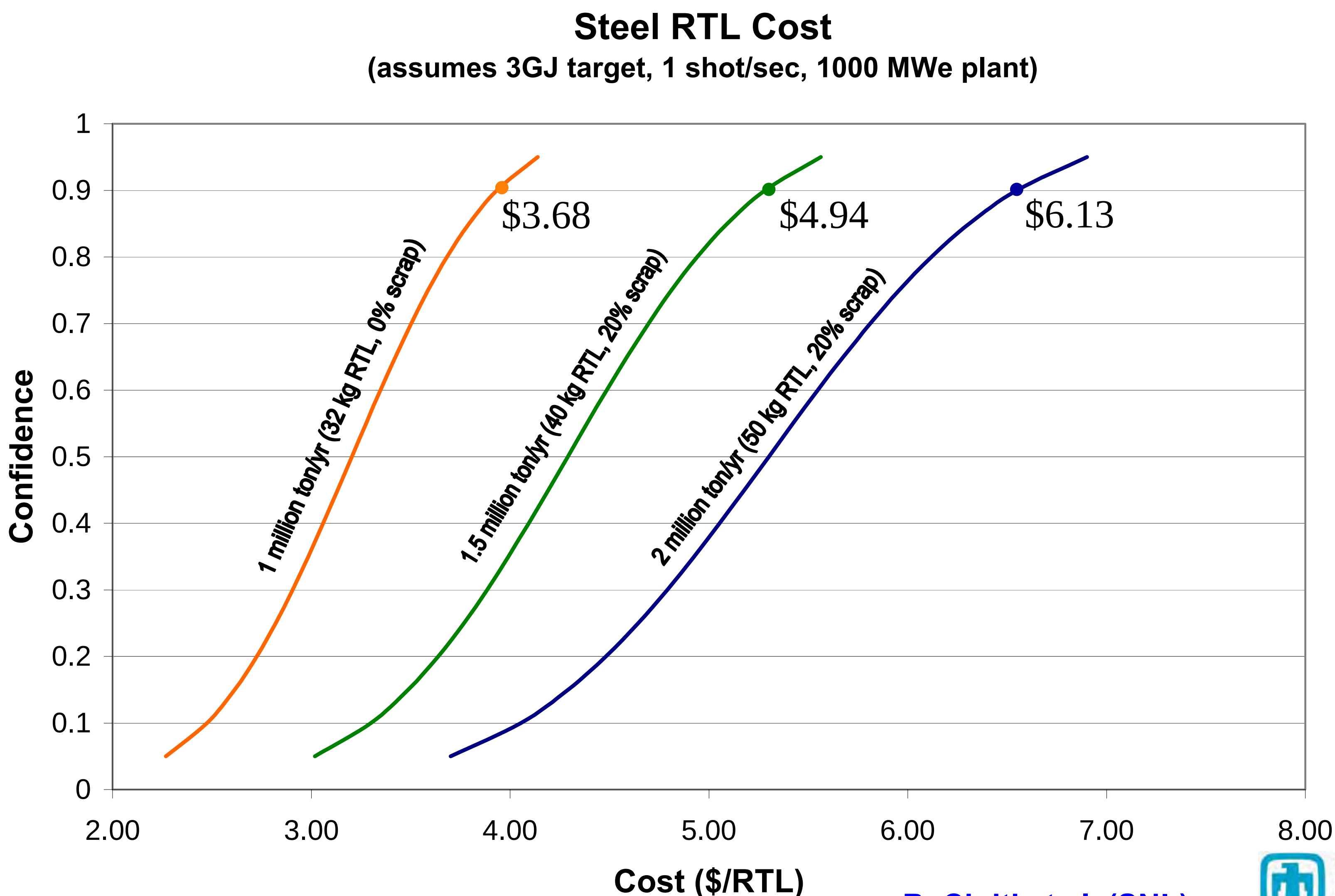
RTL Manufacturing

Furnace	Electric Arc
Production	Sheet Metal to Deep Draw
Energy Demand	184 MW for ten chambers

G. Rochau, J. Cook, B. Cipiti, et al. (SNL)

Sandia National Laboratories

Steel RTL Cost is Driven by Mass



B. Cipiti et al. (SNL)

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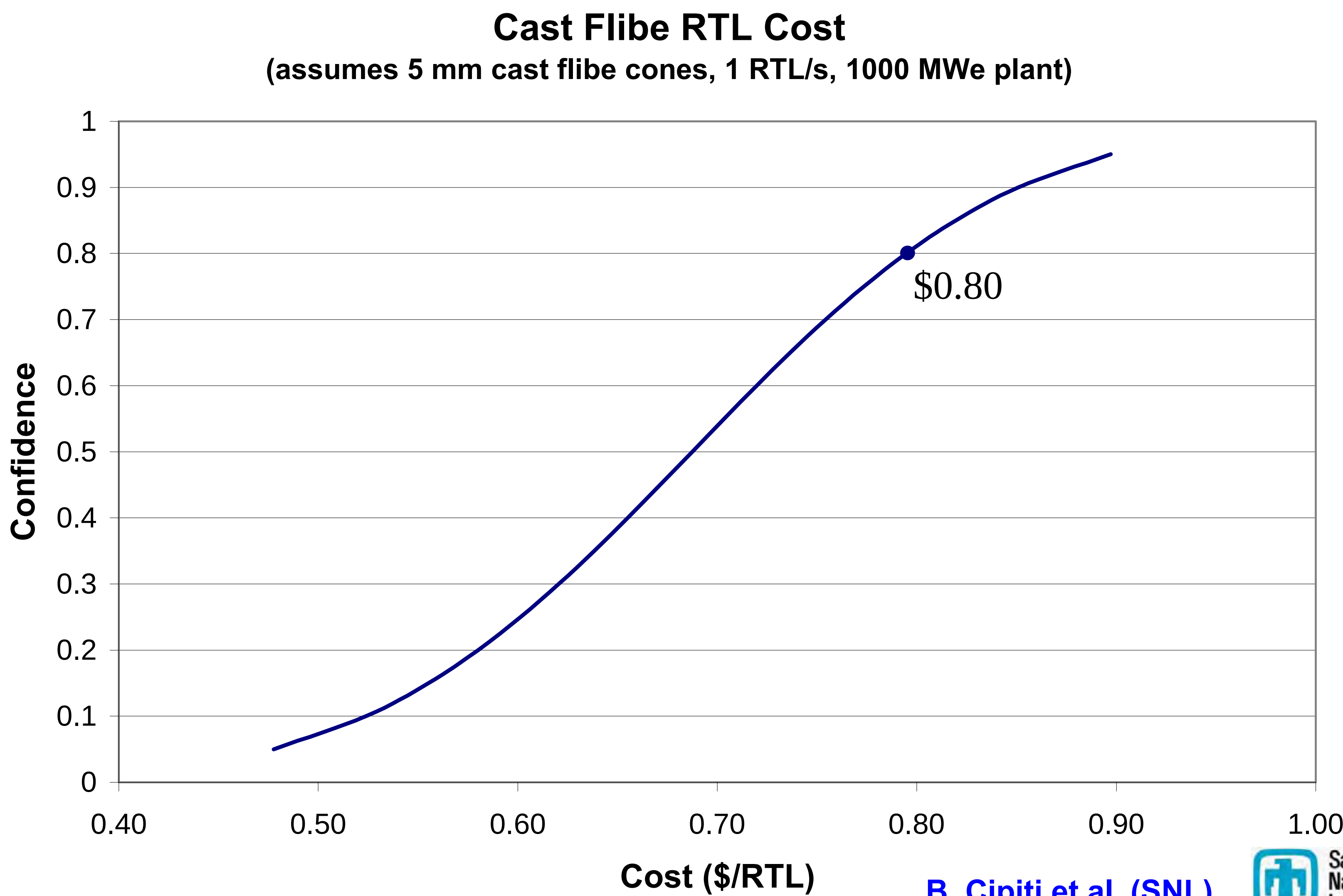
Cast Flibe RTLs Cost Considerably Less



B. Cipiti et al. (SNL)

RTL activation

Carbon steel RTL (preferred) L. El-Guebaly (U. Wisconsin)

recycle remotely in ~ 1.5 day

after 35 years, material can be released for reuse (clearance index <1)

RTL dose peaks at 160 Sv/hr, and drops to 1 Sv/hr in one hour

advanced remote handling can have up to 3000 Sv/hr

(so should have large safety margin)

Iron, or frozen Flibe W. Meier et al. (LLNL)

analyzed each element in periodic chart

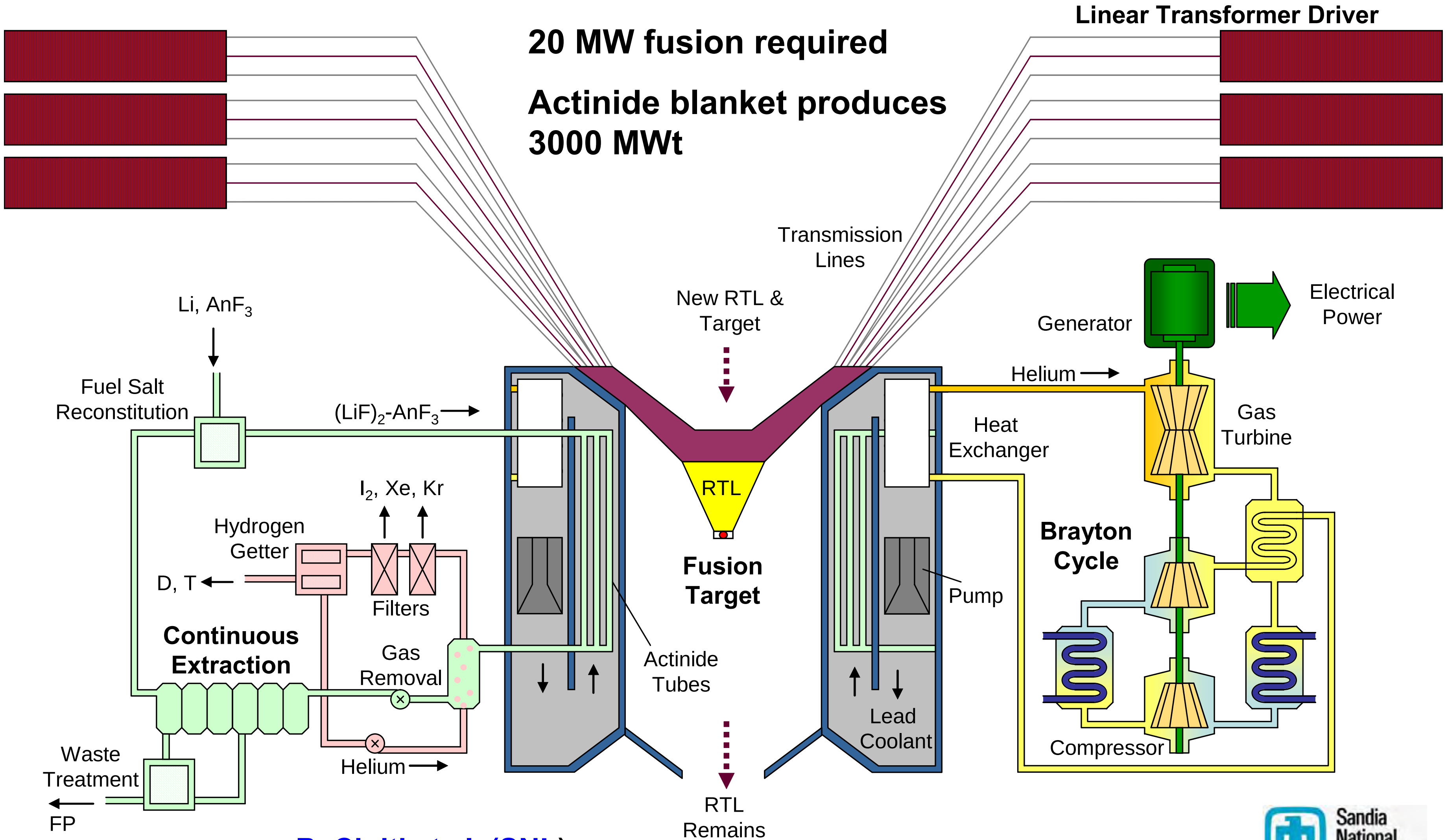
considered 1 day recycle with WDR < 1

contact dose rate in range of 10-100 Gy/hr for iron

acceptable lifetime dose to machinery for < 114 Gy/hr

(so should have some safety margin)

In-Zinerator Power Plant Concept: A Fusion-Fission Hybrid:
A sub-critical blanket burns actinides – produces transmutation of waste and produces power



B. Cipiti et al. (SNL)

Sandia National Laboratories

Current Status and Near-Term Plans

Three CDs summarize Z-IFE R&D

Z-IFE Final Report FY04 ***SAND-2005-2742P*** **(856 pages)**

Z-IFE Final Report FY05 ***SAND-2006-7399P*** **(1037 pages)**

Z-IFE Final Report FY06 ***SAND-2007-0419P*** **(1032 pages)**

Z-Pinch IFE Program
Final Report for FY04
Sandia National Laboratories
SAND-2005-2742P
(856 pages)

RTL **Z-PoP**
LTD **Targets**
Shocks **Power Plants**

SNL LLNL LANL NRL U. Wisconsin UCB UCD UCLA UNM Georgia-Tech U. Missouri-Columbia U. Alabama GA MRC EG&G Omicron SAIC HCEI-Tomsk, Russia Kurchatov-Moscow, Russia

Contact: *clolson@sandia.gov*

Z-Pinch IFE Program
Final Report for FY05
Sandia National Laboratories
SAND-2006-7399P
(1037 pages)

RTL **Z-PoP**
LTD **Targets**
Shocks **Power Plants**

SNL LLNL LANL NRL U. Wisconsin UCB UCD UCLA Georgia-Tech U. Alabama GA ATK-MRC EG&G SAIC HCEI-Tomsk, Russia Kurchatov-Moscow, Russia

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Z-Pinch IFE Program
Final Report for FY06
Sandia National Laboratories
SAND2007-0419P (1032 pages)
[Includes SAND2007-0059, SAND2006-7148, SAND2006-6590]

RTL **Power Plants**
LTD **Transmutation**

SNL LLNL LANL ANL NRL U. Wisconsin UCB UCLA Georgia-Tech U. Alabama Texas A&M GA Hobart & William Smith College Voss Scientific SAIC HCEI-Tomsk, Russia Kurchatov-Moscow, Russia

Contact: *clolson@sandia.gov*

Three Sandia Reports are the core of the FY06 Z-IFE Results

included in the FY06 CD

SANDIA REPORT
SAND2007-0059
Unlimited Release
Printed January 2007

Recyclable Transmission Line (RTL) and Linear Transformer Driver (LTD) Development for Z-Pinch Inertial Fusion Energy (Z-IFE) and High Yield

Craig L. Olson, Michael G. Mazarakis, William E. Fowler, Robin A. Sharpe, David L. Smith, Matthew C. Turgeon, William L. Langston, Timothy D. Pointon, Paul F. Ottinger, Joseph W. Schumer, Dale R. Welch, David V. Rose, Thomas C. Genoni, Nicki L. Bruner, Carsten Thoma, Mark E. Barkey, Michael Guthrie, Daniel C. Kammer, Gerald L. Kulcinski, Yuri G. Kalinin, Alexander S. Kingsep, Sergei L. Nedoseev, Valentin P. Smirnov, and Alexander Kim

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Approved for public release; further dissemination unlimited.

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SANDIA REPORT
SAND2006-7148
Unlimited Release
Printed November 2006

Z-Inertial Fusion Energy: Power Plant Final Report FY 2006

Jason T. Cook, Gary E. Rochau, Benjamin B. Cipiti , Charles W. Morrow, Salvador B. Rodriguez, Cathy O. Farnum, Marcos A. Modesto-Beato, Samuel Durbin, James D. Smith, Paul E. McConnell, Dannelle P. Sierra, Craig L. Olson, Wayne Meier, Ralph Moir, Per F. Peterson, Philippe M. Bardet, Chris Campen, James Franklin, Haihua Zhao, Gerald L. Kulcinski, Mark Anderson, Jason Oakley, Ed Marriott, Jesse Gudmundson, Kumar Sridharan, Riccardo Bonazza, Virginia L. Vigil, Mohamed A. Abdou, Lothar Schmitz, Alice Ying, Tomas Sketchley, Yu Tajima, Said I. Abdel-Khalik, Brian Kern, Said.M. Ghiaasiaan

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SANDIA REPORT
SAND2006-6590
Unlimited Release
Printed November 2006

Fusion Transmutation of Waste: Design and Analysis of the In-Zinerator Concept

B.B. Cipiti, V.D. Cleary, J.T. Cook, S. Durbin, R.L. Keith, T.A. Mehlhorn, C.W. Morrow, C.L. Olson, G.E. Rochau, J.D. Smith, M. Turgeon, M. Young, L. El-Guebaly, R. Grady, P. Phruksarojanakun, I. Sviatoslavsky, P. Wilson, A.B. Alajo, A. Guild-Bingham, P. Tsvetkov, M. Youssef, W. Meier, F. Venneri, T.R. Johnson, J.L. Willit, T.E. Drennen, W. Kamery

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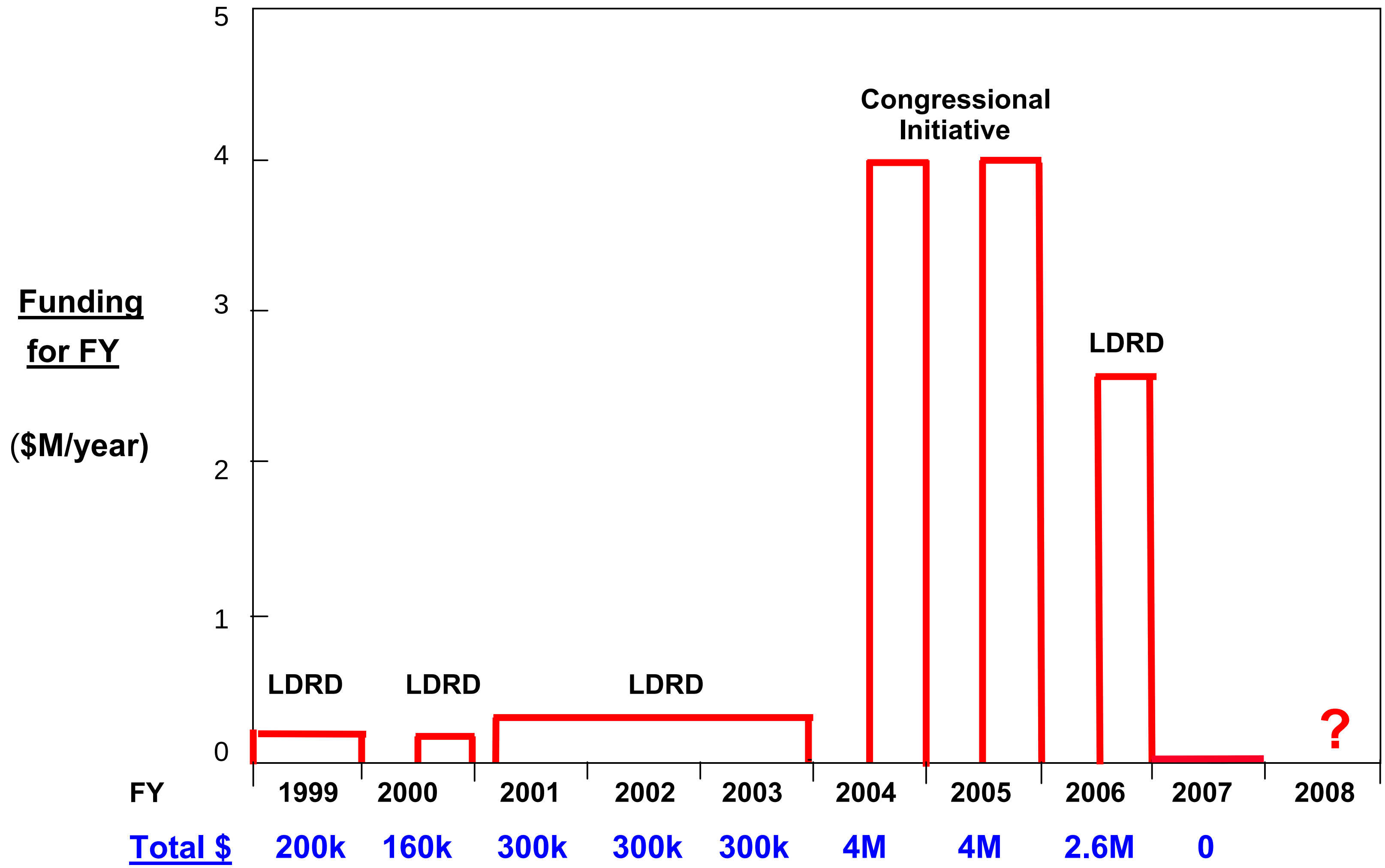
Z-IFE Funding



FY07 related work on nuclear blankets and transmutation is in the final year of a Grand Challenge LDRD (FY05-FY07)

GC LDRD Title: Advanced Fusion Concepts: Neutrons for Testing and Energy

GC LDRD Mission:

- study advanced pulsed power fusion targets on Z
- design an externally-driven nuclear assembly (Z-EDNA) driven by Z fusion neutrons for DP testing
- develop a Z-fusion nuclear waste transmutation concept

GC LDRD End States:

- enable an ICF program decision on making advanced fusion concept part of the baseline program
- enable a Sandia decision on building & fielding a Z-EDNA on ZR for DP neutron testing.
- enable Sandia to participate in international transmutation research

Z-IFE comments re: Next Step Pulsed Power Facility

DOE NNSA DP charter for SNL ICF program is to assess High Yield

A High-Yield Driver Facility should be compact, efficient, cost effective, potentially rep-rateable, and have minimum activation issues. An attractive candidate for High Yield is to:

- **Use LTD technology (Kurchatov agrees)**
- **Use RTLs (allows higher shot rate)**
- **Use single-shot thick liquid wall chamber (alleviates chamber activation issues)**

Possible Options for supporting Z-IFE in FY07

Create a "home" for IFE in DOE	not in FY07
Congressional Initiative	not in FY07
LDRD (Z-IFE is in all parts of the SNL Science of Extreme Environments LDRD call)	not in FY07
DP (do parts related to High Yield)	not in FY07
Senate mark – proposed HED Office for IFE, etc.	not in FY07
Private industry (power utilities)	too early
?	

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Of the six task areas for Z-IFE, only LTD (for a single-shot, next-step driver) will have some support in FY07

FY04 Z-IFE $4M Congressional Initiative	RTL	LTD repetitive	Shock mitigation	Z-PoP	Z-IFE targets	Power Plant	
FY05 Z-IFE $4M Congressional Inititative	RTL	LTD repetitive	Shock mitigation	Z-PoP	Z-IFE targets	Power Plant	
FY06 Z-IFE $2.6M LDRD	RTL	LTD repetitive	Shock mitigation		Z-IFE targets	Power Plant	Transmutation In-Zinerator GNEP
FY07 Pulsed Power Technology Development $??		LTD 1-shot					

Cost of ending Z-IFE Program in FY07

Loses momentum for Z-IFE gained over last 6 years

Loses expertise of 19-member Z-IFE collaboration

Loses Z-IFE constituency in fusion community

Ends Z-IFE development in all 6 task areas

Removes pressure on DOE to establish home for IFE

Loses community enthusiasm for Z-IFE

Ends University Ph.D. Thesis projects on Z-IFE (left unfinished)

Loses opportunity to be ready to capitalize for energy on NIF success

How do you see Z-IFE evolving beyond the near term?

Z-IFE is on hold, and will not evolve unless there is a change in the U.S. "un-written" policy on IFE.

Only the LTD task area may continue under NNSA support.

The potential intermediate step of transmutation will continue to be examined with final GC LDRD funding in FY07.

What needs to be accomplished to move forward?

The U.S. needs to have a “written policy” on IFE that honors the FESAC recommendations on IFE.

DOE needs to have a home and funding for IFE.

Z-IFE needs to have continuous support (not picket fence funding).

What are potential landscape-changing developments?

NIF demonstrates ignition

Energy crisis

Global warming concerns escalate dramatically

Breakthrough target results on ZR

What are the technical issues for Z-IFE?

RTL power flow, electrical conductivity (Flibe vs. steel), mass (strength vs. cost)

LTD development and demonstration

Thick liquid walls and shock mitigation

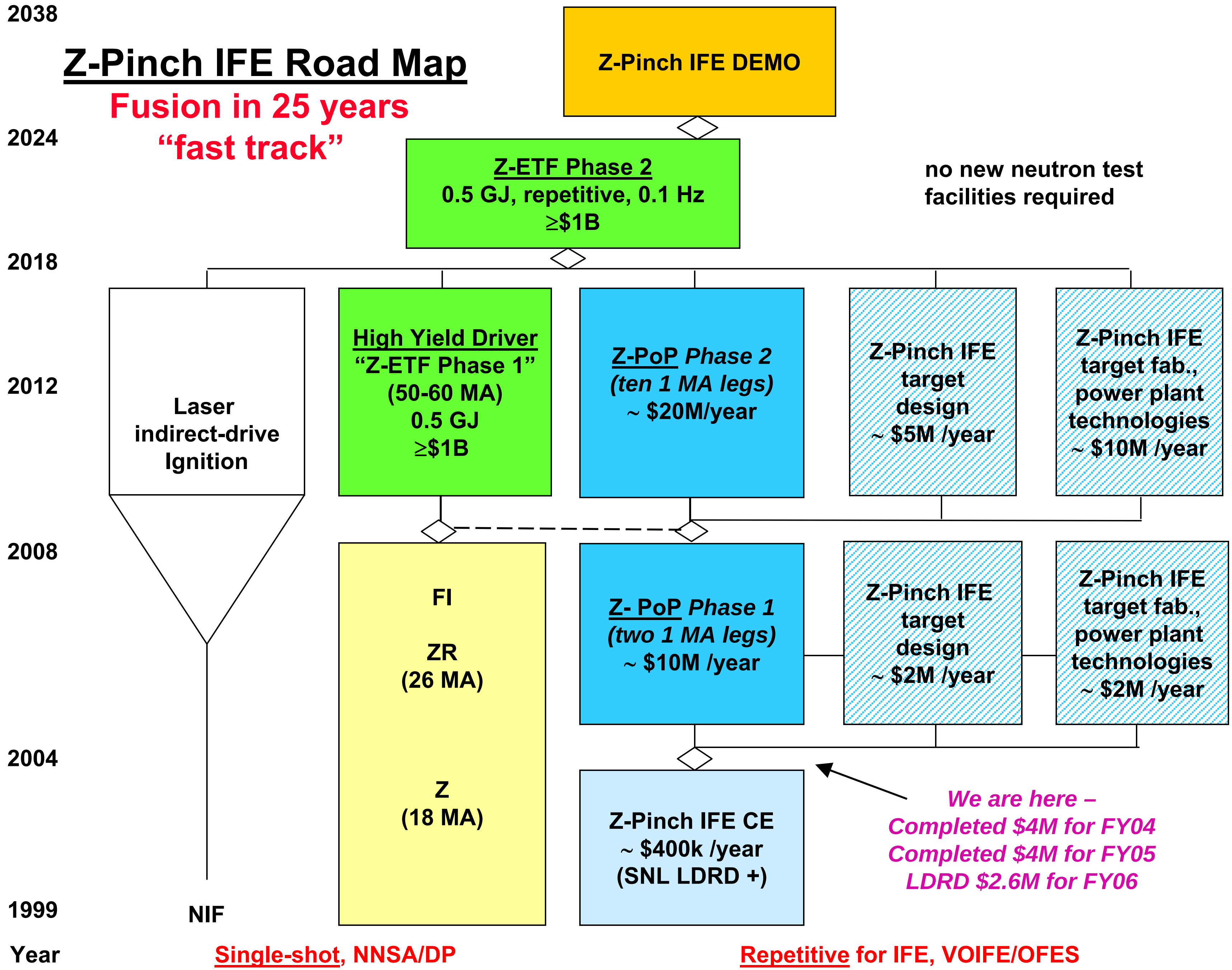
Z-IFE targets with high yield and high gain

Power plant engineering and economics

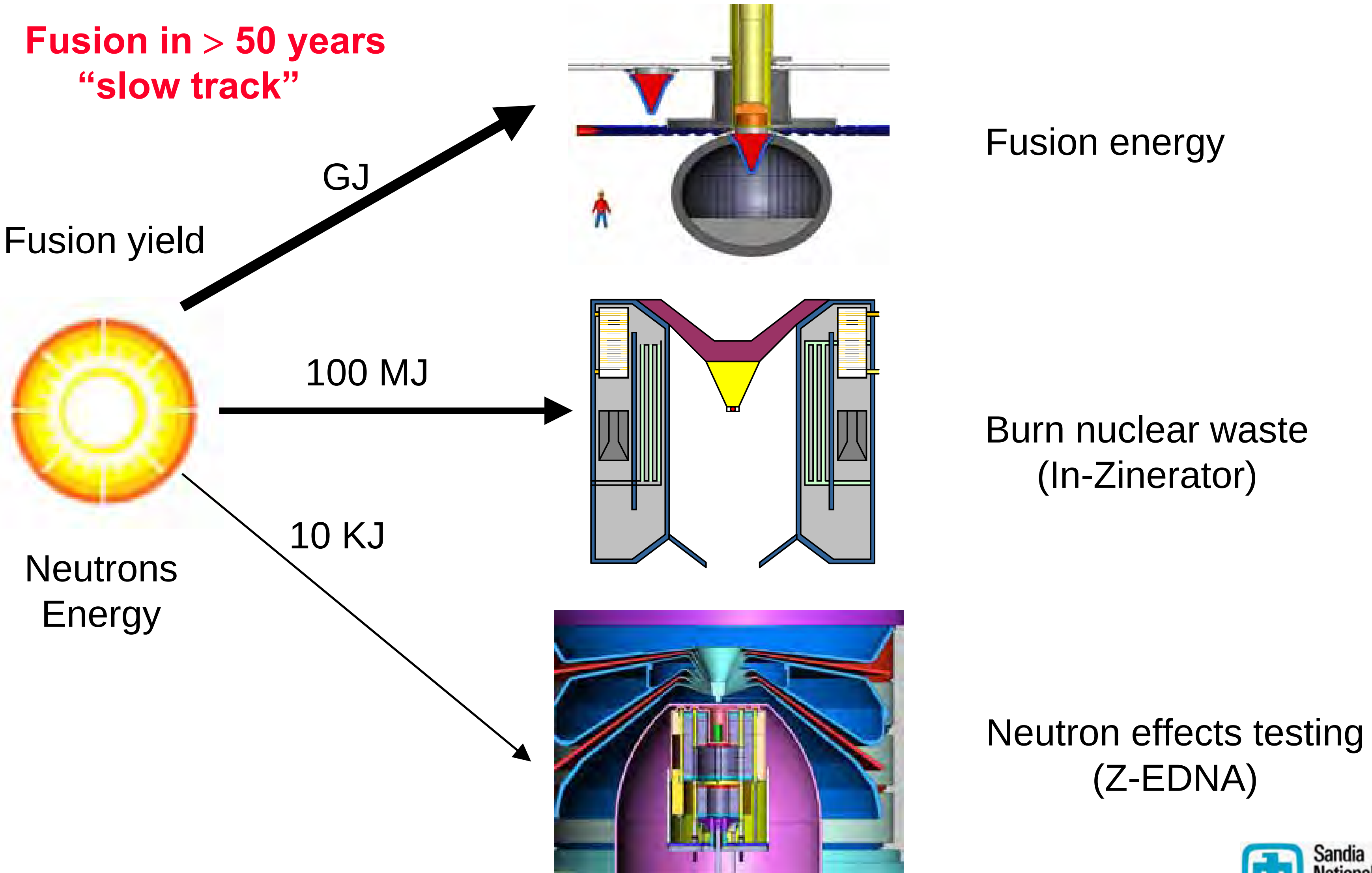
What is the present situation for Z-IFE?

- Z-IFE is on hold indefinitely
- ICF & Pulsed Power Technology programs may enable future Z-IFE
  - ICF: increase target gain "G" by advanced target design & experiments
  - Pulsed Power Technology & ICF: increase driver efficiency "η" by LTD development
- Proposed LDRD investments:
  - Fusion technology R&D, including blanket multiplication "M"
  - Power plant technology – conversion cycle efficiency "η_T"
  - System studies of yield, rep-rate and containment technology
- Be prepared for a "landscape-changing event" to re-initiate interest in Z-IFE

Long-Range Vision


Z-Pinch IFE Road Map
Fusion in 25 years
"fast track"
2038
2024
2018
2012
2008
2004
1999
Year
Z-Pinch IFE DEMO
Z-ETF Phase 2
0.5 GJ, repetitive, 0.1 Hz
≥$1B
no new neutron test facilities required
Laser indirect-drive Ignition
NIF
High Yield Driver
"Z-ETF Phase 1"
(50-60 MA)
0.5 GJ
≥$1B
Z-PoP Phase 2
(ten 1 MA legs)
~ $20M/year
Z-Pinch IFE target design
~ $5M /year
Z-Pinch IFE target fab., power plant technologies
~ $10M /year
FI
ZR
(26 MA)
Z
(18 MA)
Z- PoP Phase 1
(two 1 MA legs)
~ $10M /year
Z-Pinch IFE target design
~ $2M /year
Z-Pinch IFE target fab., power plant technologies
~ $2M /year
Z-Pinch IFE CE
~ $400k /year
(SNL LDRD +)
We are here –
Completed $4M for FY04
Completed $4M for FY05
LDRD $2.6M for FY06
Single-shot, NNSA/DP
Repetitive for IFE, VOIFE/OFES

Fission-fusion hybrids could provide a technology maturation path to fusion energy



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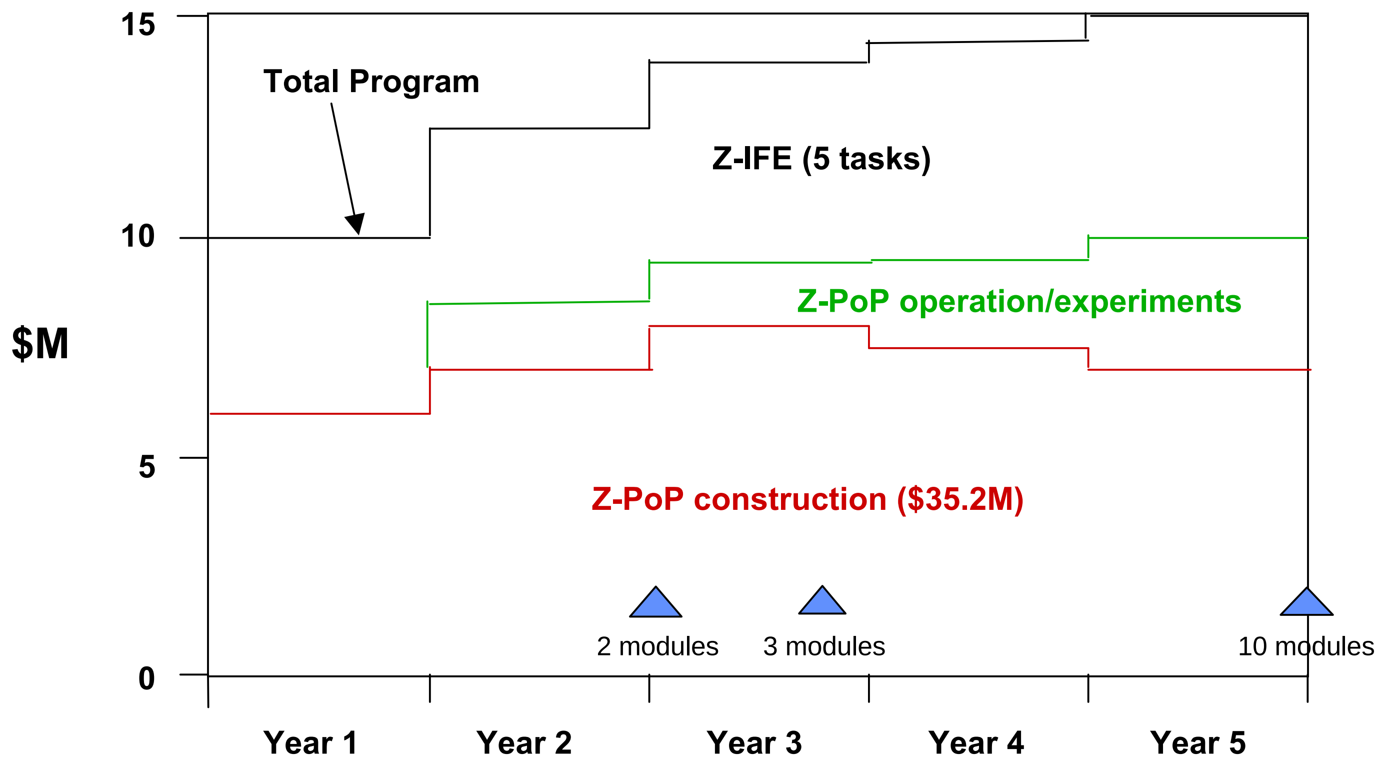
Funding needs for Z-IFE to move to next step:

- minimal program: $2.6M – $4M per year
- robust program including Z-PoP:
  ~ $12M/year

Z-IFE / Z-PoP Funding Profile



Z-IFE (Z-Pinch Inertial Fusion Energy)

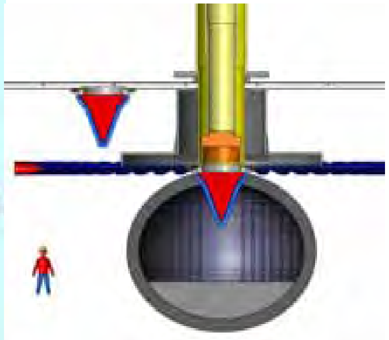
Z-IFE Results
Current Status and Near-Term Plans
Long-Range Vision
Funding needs to move to the next step

RTL

LTD driver

Shock Mitigation

Z-PoP

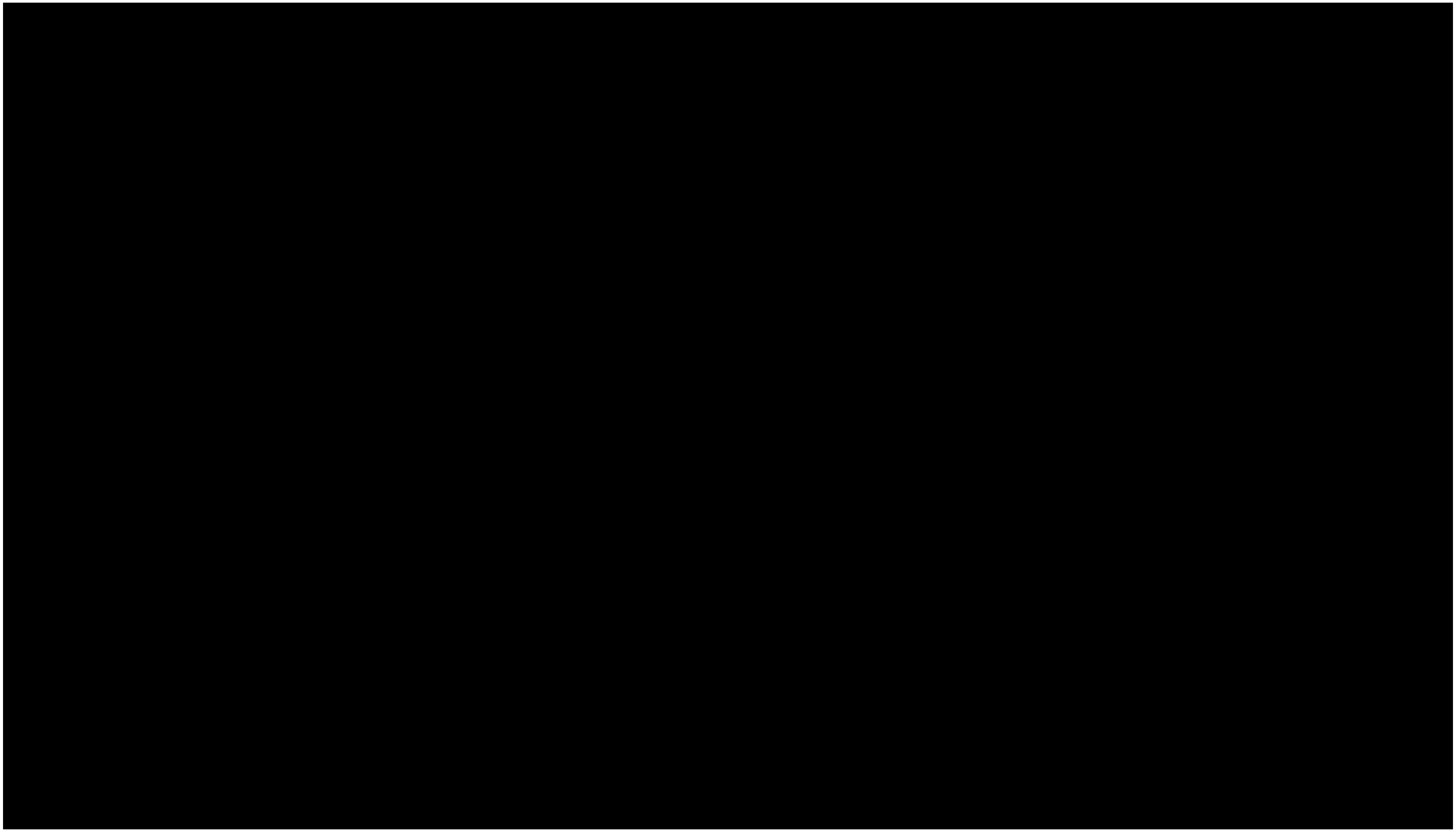


Chamber

Present results (three CDs) assure us that Z-IFE is on a sound scientific and engineering basis. The rate at which Z-IFE may be realized depends on the importance the U.S. places on IFE.

Extra View-Graphs

Z-PoP Movie



Z-IFE Presentations at ANS TOFE (November 2006)

(1) "Z-Pinch Inertial Fusion Energy (Z-IFE) Program"
Craig L. Olson, SNL (**Invited** Plenary)

(2) "Keeping the Cryogenic Targets Layered Until Shot Time in a Z-Pinch IFE Power Plant"
Remy Gallix, et al., GA

(3) "Modeling of Z-IFE Hydrogen Plants with MELCOR-H2"
Sal Rodriguez, et al., SNL, Purdue, and Omicron

(4) "Systems Modeling for Z-IFE Power Plants"
Wayne R. Meier, LLNL

(5) "Shock Mitigation Using Compressible Two-Phase Jets for Z-Pinch IFE Reactor" Applications"
Celine C. Lascar, et al., Georgia-Tech

(6) "Void Fraction Distribution in Two-Phase Jets for Z-Pinch IFE Reactor Applications"
Brian J. Kern, et al., Georgia-Tech

(7) "Shock Mitigation Studies in Voided Liquids for Fusion Chamber Protection"
Virginia L. Vigil, et al., SNL and University of Wisconsin

(8) "Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant"
Laila A. El-Guebaly, et al., University of Wisconsin

(9) "The 500 kA, 100 ns LTD Cavity Has Reached the 0.1 Hz Repetition Rate Z-Pinch IFE Goal"
William E. Fowler, et al., SNL

(10) "Z-Pinch Fusion Driven Systems for IFE, Transmutation, and GNEP"
Gary E. Rochau, SNL (**Invited**)

(11) "Z-Pinch Chamber Assessment and Design"
Igor Sviatoslavsky, et al., University of Wisconsin

(12) "Engineering Issues Facing Transmutation of Actinides in a Z-Pinch Fusion Power Plant"
Paul P. H. Wilson, et al., University of Wisconsin

(13) "The Sandia High Current High Voltage Z-Pinch IFE Driver Program"
Michael G. Mazarakis, et al., SNL and HCEI, Tomsk, Russia (**Invited**)

(14) "Power Flow Constraints for a Recyclable Transmission Line for Z-Pinch IFE"
Joseph W. Schumer, et al., NRL and SNL

(15) "Driver Transition Geometries and Inductance Considerations Leading to Design Guidelines for a Z-IFE Power Plant"
David L. Smith, et al., SNL

(16) "Transmutation of Actinides Using Z-Pinch Fusion"
Benjamin B. Cipiti, et al., SNL and University of Wisconsin (**Invited**)

(17) "Isotopic Anaylsis of the In-Zinerator Actinide Management System"
Phiphat Phruksarojanakun, et al., University of Wisconsin and SNL (**Invited**)

(18) "Parametric Analysis of Z-Pinch Driven Nuclear Waste Incineration System"
Avery A. Guild-Bingham, SNL and Texas A&M

(19) "Three-Dimensional Nuclear Assessment for the Chamber of Z-Pinch Power Plant"
Mohamed E. Sawan, et al., University of Wisconsin (**Invited**)

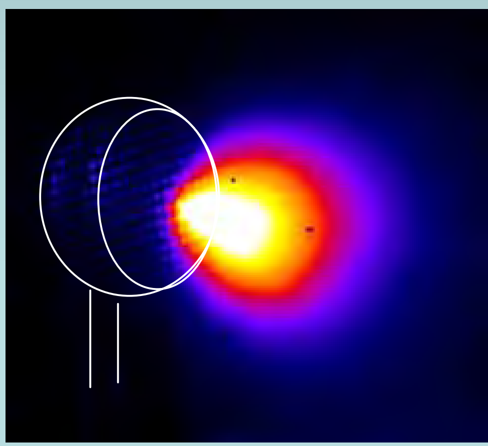
(20) "Investigation of Argon and Xenon as Potential Shock Attenuators in Z-IFE Chambers Using ALEGRA"
Sal Rodriguez, et al., SNL

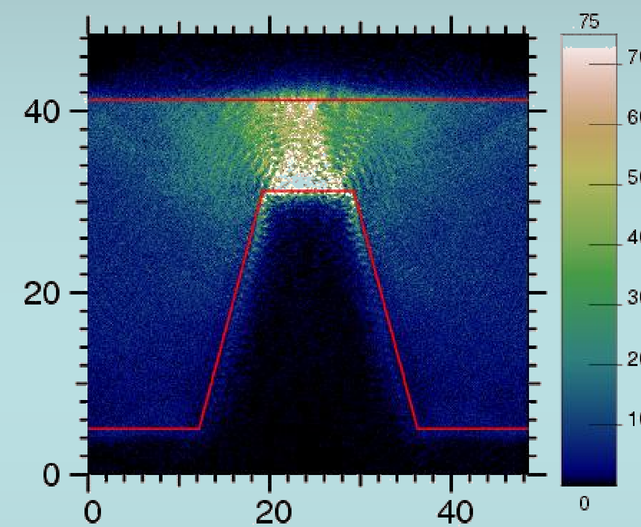
(21) "Simple Models for the Dynamic Response Associated with IFE Shock Mitigation"
R. Jeffrey Lawrence, et. al., SNL

(22) "Experimental Investigation of Z-Pinch IFE Chamber Liquid Structure Response"
Per F. Peterson, et al., UCB and LLNL

(23) "Fusion Power Plant Tritium Production and Recovery"
Rodney L. Keith, SNL

Fast Ignition – Extreme Science and Fusion





E. Michael Campbell

IFE Strategic Planning Workshop

San Ramon, Ca

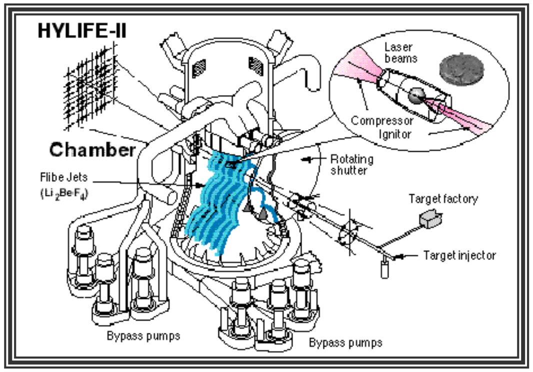
April 24 2007

Questions for the Workshop

- **How does Fast Ignition evolve beyond the near term?**
- **What needs to be accomplished to move forward?**
- **What are potential “landscape-changing” developments?**

Fast Ignition has numerous attractive features in addition to high gain at lower total drive energy

- Compression can be done with all Drivers (longer λ lasers (?))
- Brightness requirements for compression drivers are reduced
- target fabrication tolerances are relaxed (needs to be quantified)
- Direct and Indirect target schemes for compression
- Innovative target concepts
  - one-sided indirect driver (I.e. (no beam bending for HIF)
  - asymmetric compression drive configurations
    - indirect drive illumination for direct drive



Innovative reactor concepts are **possible-integrated system optimization is required!**

How does Fast Ignition evolve beyond the near term?

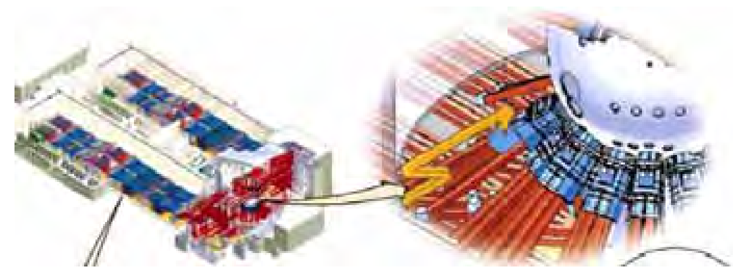
Advances over the past several years has triggered worldwide interest in and possibilities for FI

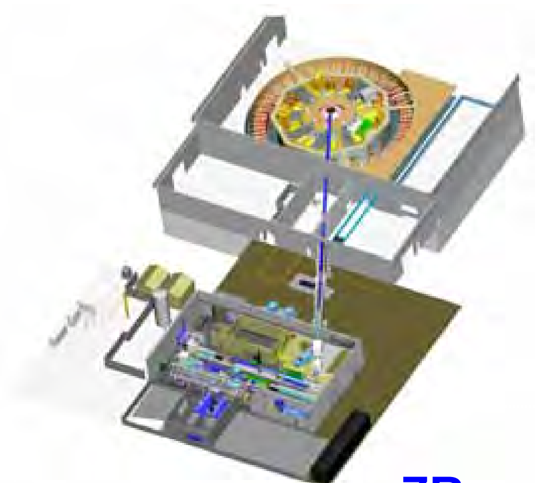
- Nova Petawatt
  - “kilojoule class PW beamlines are possible
- Osaka Experiments
  - ~20-30% coupling of ignitor laser to core
  - Motivated FIREXI and raised international interest (2006 Excellence Award)
- Laser technology advances
  - OPOCPA
  - Large aperture damage resistant dielectric gratings
  - “aperture combining”or grating tiling
- NNSA mission motivation for PW lasers
  - Radiography
  - HEDP

New Facilities will allow FI physics to be explored under relevant conditions

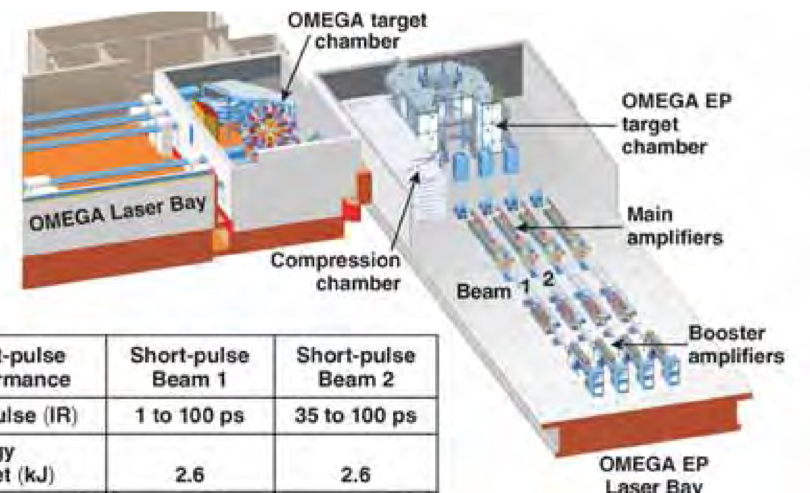
FIREX-1(Japan)

NIF/ARC (NNSA)





ZR and Petawatt (NNSA)



Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	> 80% in 20 μm	> 80% in 40 μm

Omega-EP (NNSA)

OFES has developed a multi-institutional FI program

- **Broad based US partnership**
  - University (<u>UR</u>, OSU,UCD,UCSD,UNR),
  - National laboratory (<u>LLNL</u>, SNL, LANL),
  - Industry (GA) research partnership
  - Coordinated with FSC and NNSA activities
- **Leverage resources with Fusion Science Center**
  - Academic partners work together
  - More access to facilities
  - Student support
- **International Collaborations**
  - FIREXI (Osaka)
  - Vulcan PW (RAL)
- **Complete science capability**
  - Modeling - hydro, LPI, PIC
  - Diagnostic development
  - Target development & fabrication

Facilities and much of "infrastructure" are not required from OFES

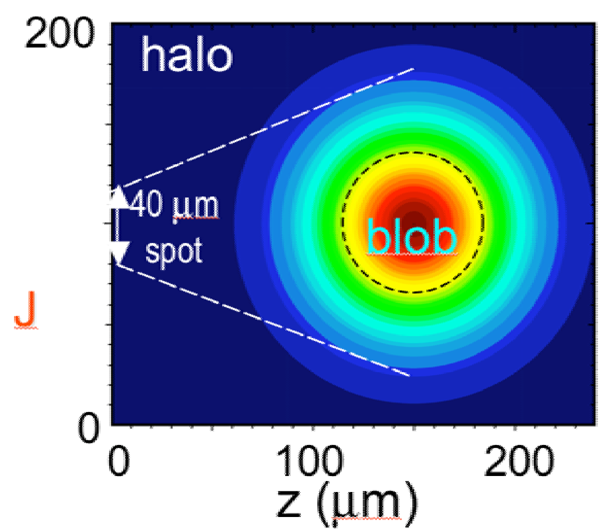
Why FI in OFES

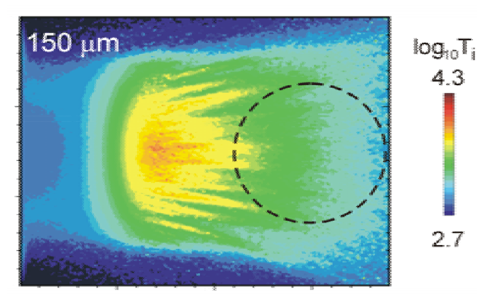
- **Strong international component**
  - **Japan is a world leader-** opportunity for formal collaboration!!
  - **Europe is a major player**
    - **Hyper proposal**
- **University involvement in integrated program**
  - **~15 students and 5 post-docs in existing program**
- **Science of the extreme**
  - **Connections to other OS programs (i.e. laser accelerators, ion accelerators)**
  - **High risk approach**
    - **NNSA present Focus to support SSP is indirect drive with direct drive as a back-up**
    - **NNSA is “mission” driven agency-the mission is the nuclear deterrent**

FI is an opportunity for significant cooperation/collaboration between OS and NNSA

Fast Ignition is a science of extremes

- **DT fuel**
  - —**Assemble 3 g/cm^2 at T< 1keV in 10 ns from 1 mm shell**
- **electrons**
  - —**Create with ~1 MeV in 10 ps in < μm thick region**
- **Generating a current into the fuel**
  - — **I ~ 6 GA current (~10^5 I_{alven}) in 40 μm dia**
  - —**surrounded by Ggauss field (if uncompensated)**

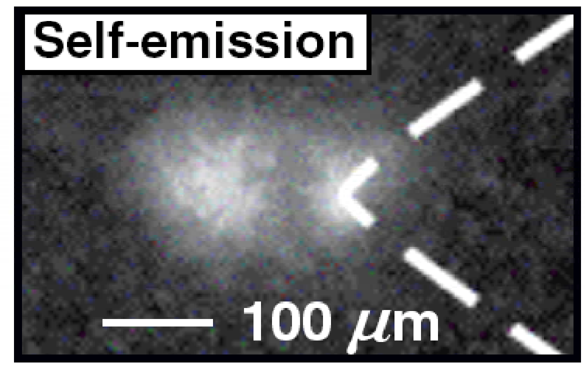




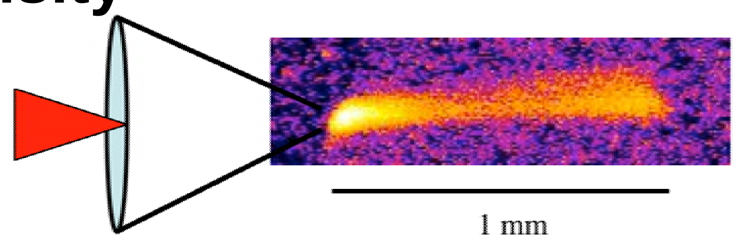
Honrubia et al

Approaching those extremes with existing capabilities

- DT fuel
  - —Assembled CH surrogate at 0.26 g/cm^2 10% of ignition ρR (7% with cone target)



- electrons
  - —Created with appropriate energy ~1% of needed number into metal
- current into the fuel
  - — Currents ~1% of needed density into metal

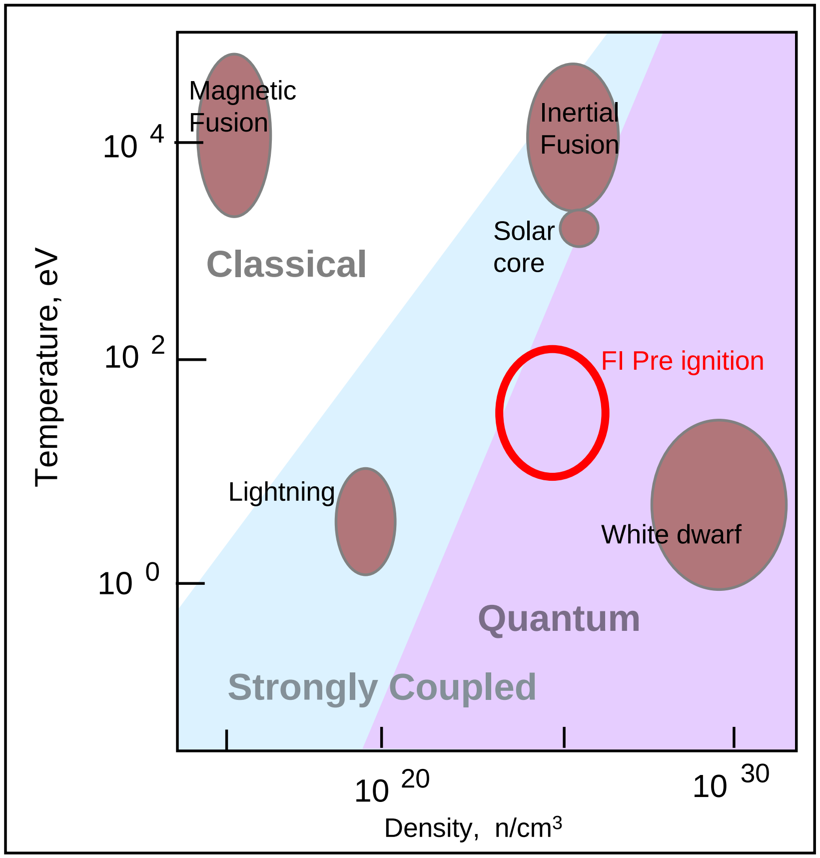


CuKα Xray fluorescence image

This has proved a rich area to investigate

- **Fundamentally different optimization problem**
  - Uniform fuel assembly (Not 1D!)
  - But require access to place ignition energy into core
- **That severely stretch capabilities**
  - Probe dense plasmas w/ high temporal and spatial resolution
  - Coupling hydro, LPI, and transport simulations
- **And connects to important science & technology**
  - Laser produced ions (compact accelerators)
  - Laser electron accelerators
  - Astrophysics
  - Warm dense matter (pre-ignited assembled fuel)
  - Relativistic laser-plasma physics

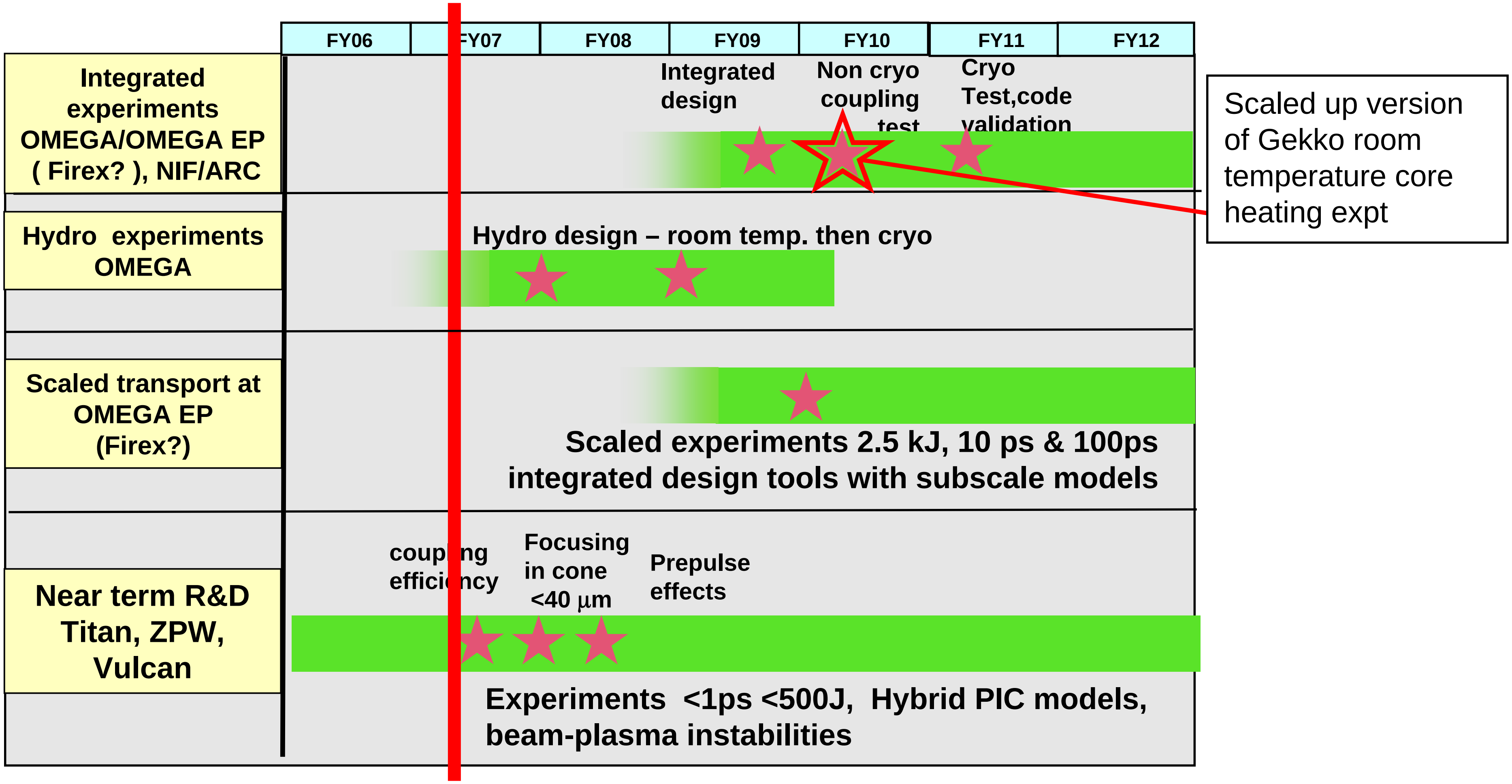
Pre-ignited FI cores are very interesting plasmas



The present experimental plan takes advantage of new capabilities in the US

- **Titan - available now**
  - —Subscale LPI transport, and preplasma effects:
  - —180J, 0.4 ps to 330J >10 ps
  - —350J, 3ns @ 2w
- **ZR-ZPW - available early FY09**
  - —Hot plasma transport expts
- **OMEGA compression – available now**
  - • Fuel Assembly
- **OMEGA EP – available beginning FY09**
  - —2.5 kJ 10 ps and 2.5kJ 100 ps
  - —Channeling and cones, hot plasma transport,
- **OMEGA/OMEGA EP - available early FY09**
  - —30 kJ compression for transport and integrated expts
- **NIF-ARC - first operational FY09**
  - —Scaled up fuel assembly, integrated tests

Plan is phased to match availability of facilities - culminates in integrated designs and experiments



Experiments over the next several years should determine the size of the ignitor laser at relevant pulsewidths and plasmas!

- E_{ig} (kJ) ~140 $(100/\rho)^{1.85}$ η^{-1}
  - ρ ~ 200-400 g/cc then E_{ig} (kJ)~(9-35) $/\eta$
- ρ ~200-400 g/cc is required for main fuel in conventional ICF
  - Goal of Omega in ~2006-2007 (Cryo target system in place!)
  - Goal of NIF in ~2010
- PW development goal is 3-5 kJ /aperture with ~10-20 psec pulses
  - If η ~0.3 : ignitor laser of ~30 to 100 kJ

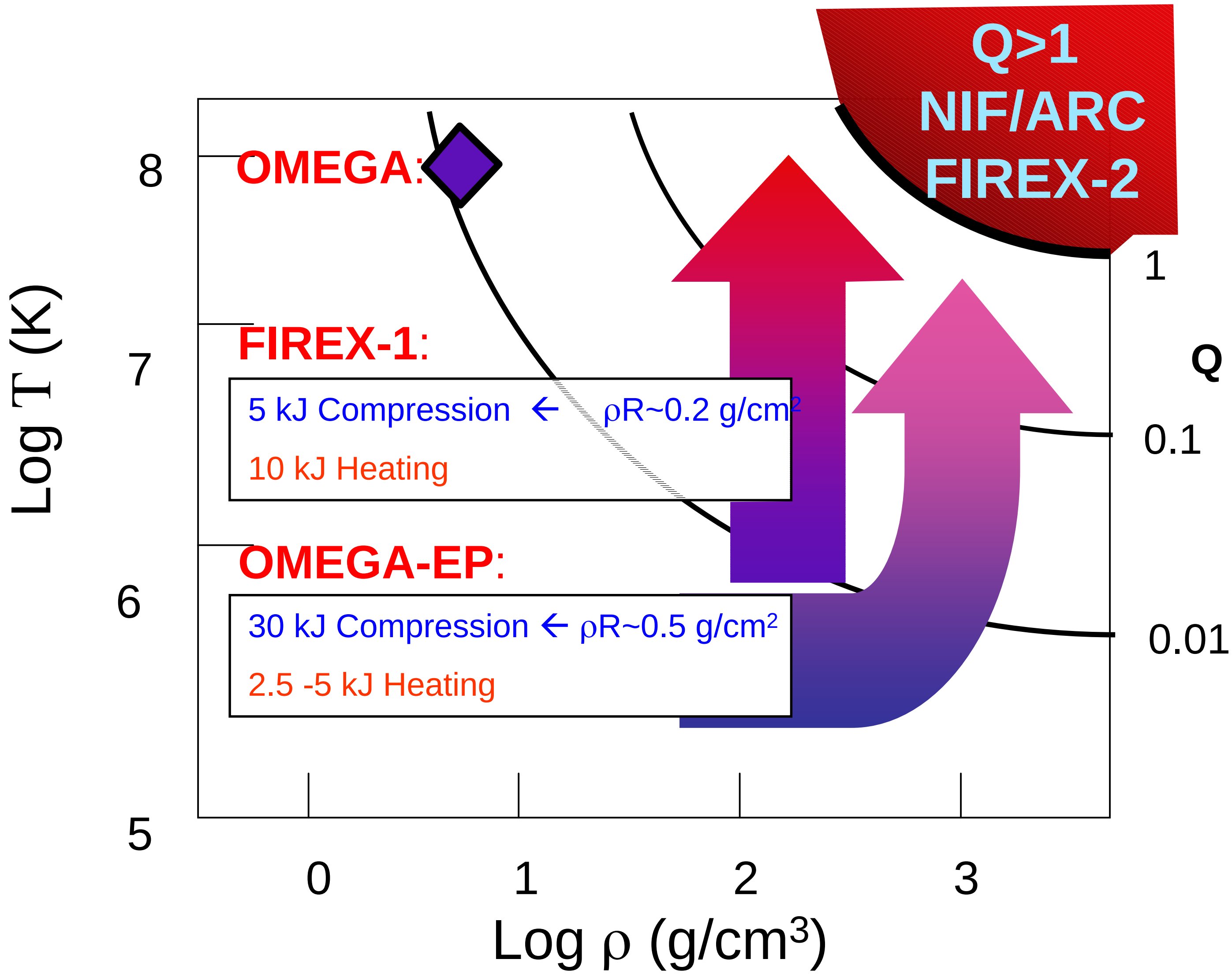
These experiments will determine η at relevant parameters for FI with $Q(E_F/E_L)$ ~10-50% if η ~30% !

The challenge is to ignite the fuel and several approaches are still being explored

- **Electron driven**
  - **Cones**
  - **Channeling**
- **Ion driven**
- **Impact foil**
- **Strong shock**

Research over the next several years –in **relevant plasmas** should determine the options (funding dependent)

FI is one ICC that has a realistic chance to be tested over the next decade!

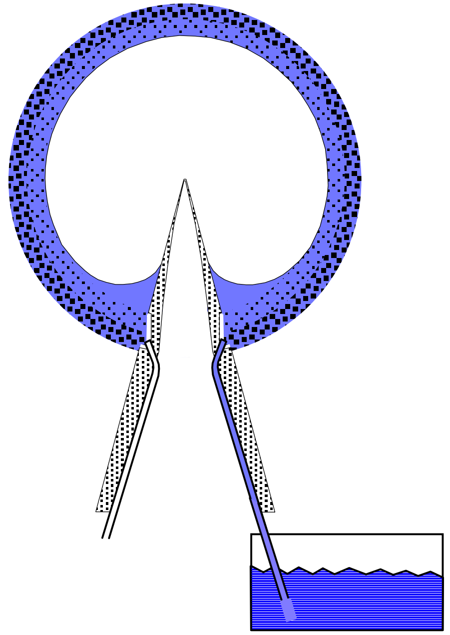


What are the challenges to realize this opportunity?

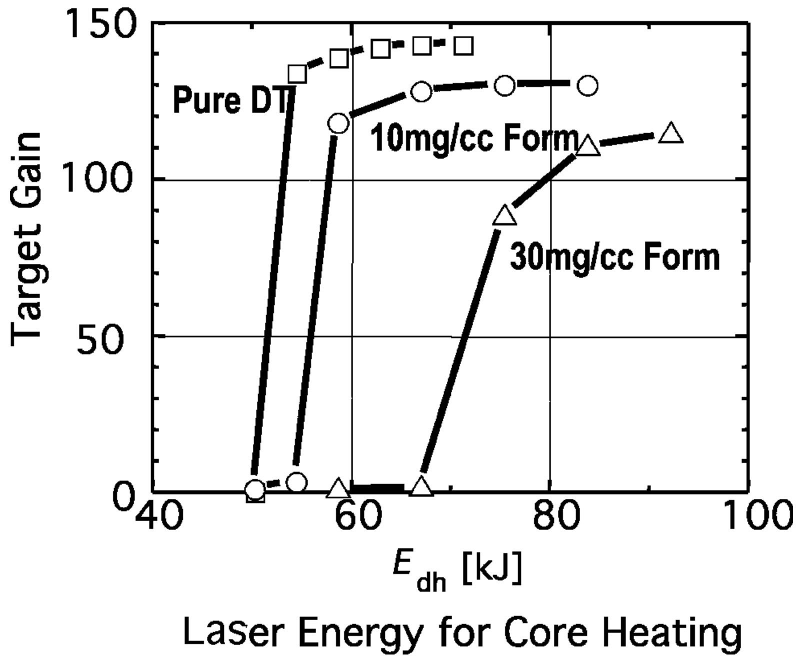
- **OFES program is multi-institutional**
  - **Coordination is a challenge- learn from NIC**
- **International collaboration should be advocated and championed at high levels of OS-only way Japan will listen!**
  - **FIREXI is focused on FI!**
- **Funding levels are insufficient to execute program and leverage NNSA investment**
  - **$10M/yr is required (present funding is ~$3.5M)**
- **Adequate facility time at NNSA facilities**
  - **~10% of Omega/Omega-EP for example (detailed program plan is required)**
- **New facilities must successfully operate!**

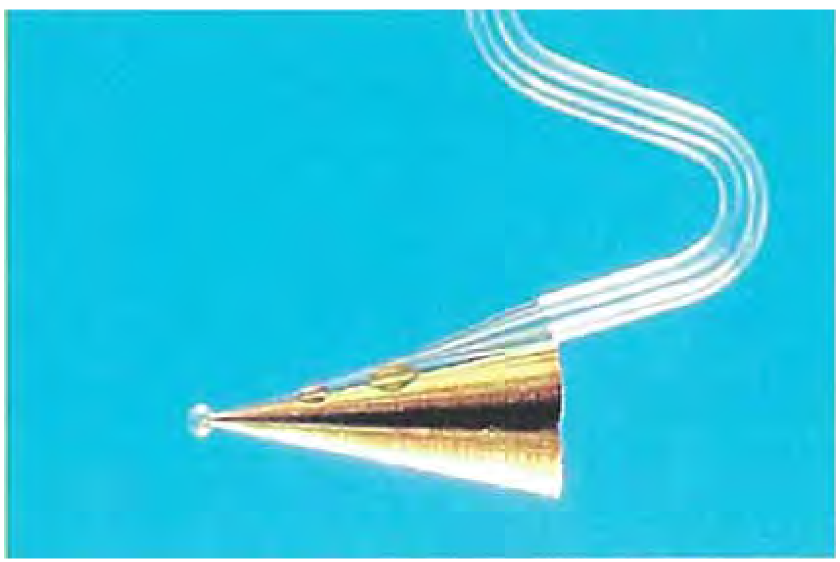
FI benefits from international R&D efforts

Foam-formed ice layers are being developed at ILE



- **Reentrant cones cause potential problems with beta layering.**
- **DT surface can be formed by filling foam**
  - **Previous cryo-foam experience at ILE**





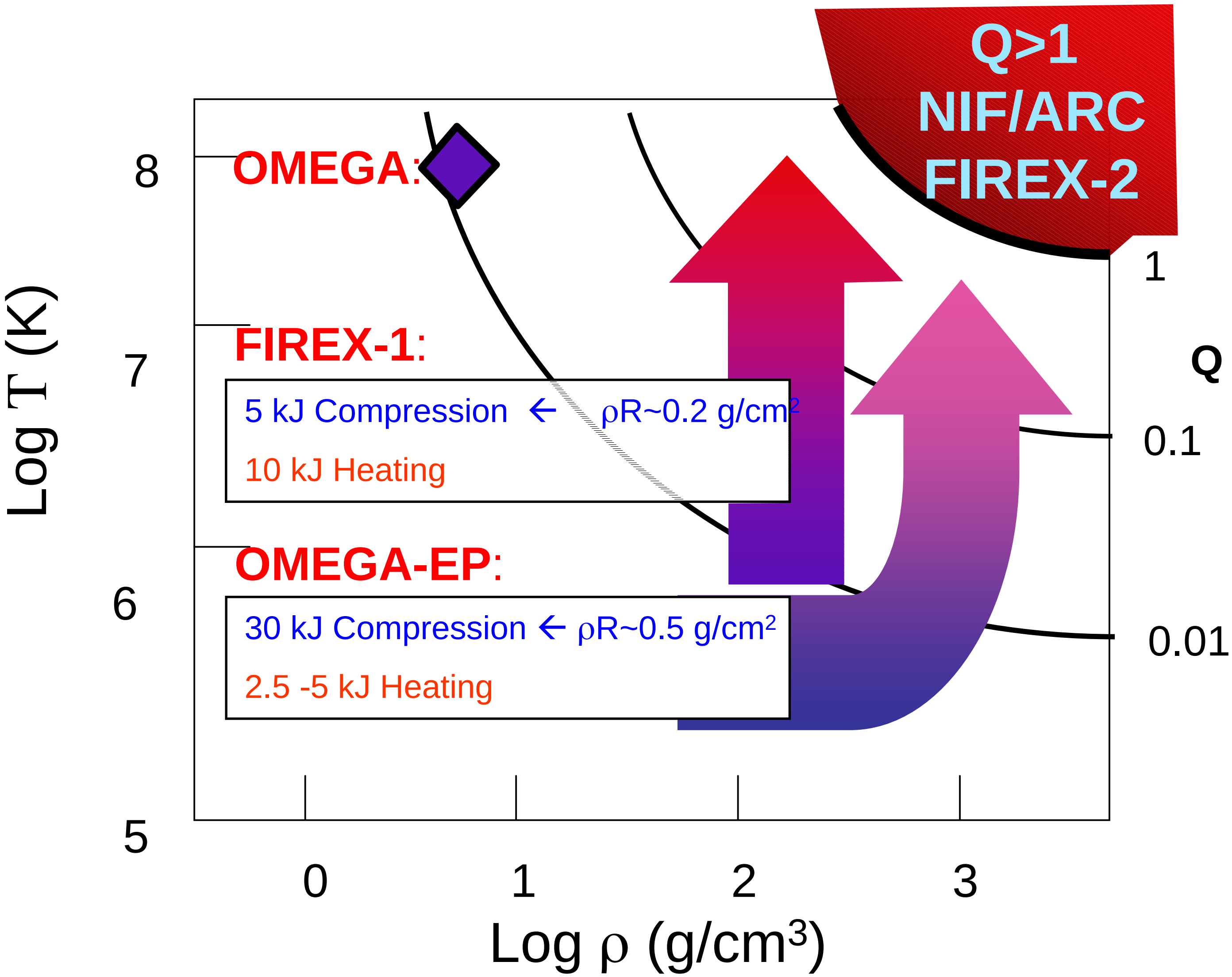
What are potential “landscape-changing” developments?

Landscape Changes for FI

- **PRL level**
  - **FI fuel assembly**
- **Science/Nature**
  - **~kilojoule scale-up of GEKO ~100 joule heating experiments**
  - **CD shells**
- **NYT**
  - **Q~ 0.5 with cyro targets**

Ignition on NIF will trigger broad interest in IFE

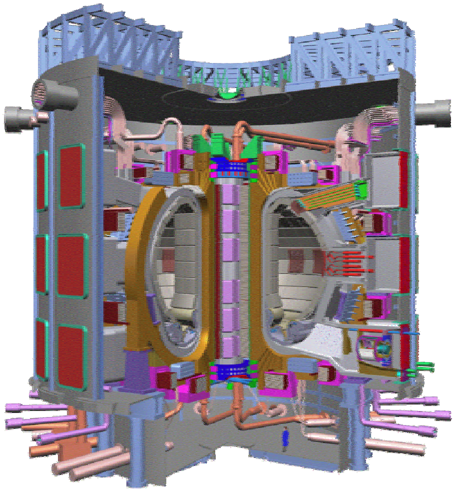
FI is one ICC that has a realistic chance to be tested over the next decade-will this opportunity be taken?



What are the credible time scales for Fusion?

- **1950-2010**
  - **- Physics of plasmas - creation, manipulation and control of fusion-relevant plasmas**
- **2010-2030**
  - **Physics of "burning plasmas" in ITER, NIF, LMJ**
    - **the equivalent "Fermi demonstration"for fusion**
- **2010-2050**
  - **Engineering and materials science of fusion energy**
    - **Integrated Plasma-Fusion (Demo 1)**
    - **Tritium breeding**
- **2040-2070**
  - **Fusion power-plant demonstration & maturation (Demo II)**
    - **"Overnight" construction costs**
    - **O&M**
    - **Availability**
- **2080-**
  - **- Significant commercial deployment**

NIF



ITER

The potential benefit of magnetic field in IFE

R.E. Siemon, B.S. Bauer, & I.R. Lindemuth, UNR

& Magneto-Inertial Fusion Community

IFE Strategic Planning Workshop

San Ramon, California

April 24, 2007

Abstract

The mainline path to fusion energy is based on the established fact that magnetic fields significantly improve the insulation of thermonuclear fuel from its surroundings. Can the same insulation improve the performance of inertially confined systems? A body of theoretical literature suggests that it can. Experiments under development will extend tests of the concepts of magneto-inertial fusion to high energy density regimes.

The potential benefit of magnetic field in IFE

1. How can magnetic field benefit fusion?
2. What is magneto-inertial fusion (MIF)?
3. Can MIF provide economical energy?
4. What research is underway?

Fermi recognized intense pulsed **B** could reduce thermal conduction

Enrico Fermi, "Super Lecture No. 5--Thermal Conduction as Affected by a Magnetic Field," Los Alamos Report 344, Sept. 17, 1945.

"A possible method of cutting down the conduction to the walls would be the application of a strong magnetic field, H. This tends to make the electrons go in circles between collisions, so impedes their mobility. Actually, it makes them go in spirals, and does not reduce the conductivity parallel to H but only to the other two dimensions, so one would probably want to design the container elongated in the direction of H, or even toroidal... with the lines of force never leaving the deuterium... rather large fields will be required... thus a field in excess of 20,000 gausses would help reduce conduction loss. While it would not be possible to produce such fields in a large volume in a steady state,the technical problem of making the field is much aided by the fact that the time during which the field is needed is much shorter than the usual relaxation time of magnetic fields, so it need be applied only instantaneously."

Effects of a strong magnetic field on ICF target hot-spot parameters

FSC

UR LLE

- LILAC simulation of NIF 1.5 MJ, direct-drive point design* $\rho_{hs} \approx 30$g/cc, $T_{hs} \approx 7$keV (before ignition), $r_{hs} \approx 50\mu$m.

- Braginskii conductivity used, anomalous effects not considered.

At 10 MG compressed field:		At 100 MG:	
$\beta \approx 4 \bullet 10^4$	$\kappa_\perp \approx 0.2\kappa_{\|\|}$ for $\omega_{ce}\tau_e \approx 1.2$	$\beta \approx 4 \bullet 10^2$	$\kappa_\perp \approx 0.01\kappa_{\|\|}$ for $\omega_{ce}\tau_e \approx 12$
r_α=270 μm	$r_\alpha/r_{hs} > 5$	r_α=27 μm	α-particles magnetically trapped: $r_\alpha/r_{hs} \approx 0.5$

Tens of MG magnetic field is needed for effective reduction of the hot-spot thermal losses through magnetic insulation.

O.V. Gotchev, N.W. Jang, J.P. Knauer, M.D. Barbero, D.D. Meyerhofer & R. Betti, UR-LLE
R.D. Petrasso & C.K. Li, *MIT Plasma Science and Fusion Center*

Comparing loss rates with fusion rates identifies the density-temperature space where fusion gain can be achieved

- $\dot{Q}_{loss} = \dot{Q}_{TC} + \dot{Q}_{RAD}$

$$\dot{Q}_{RAD} = C_{RAD} n_i^2 T^{1/2} \quad \text{(Bremsstrahlung)}$$

$$\dot{Q}_{TC} = -\nabla \bullet (K \nabla T) \quad (K = \text{thermal conductivity})$$

- **Radiation losses determine a minimum temperature:**

$$\frac{\dot{Q}_{FUS}}{\dot{Q}_{RAD}} = \frac{\varepsilon_{FUS} n_i^2 \frac{\overline{\sigma v}}{4}}{C_{RAD} n_i^2 T^{1/2}} = \frac{\varepsilon_{FUS} \frac{\overline{\sigma v}}{4}}{C_{RAD} T^{1/2}}, \quad \text{independent of } n_i \qquad \frac{\dot{Q}_{FUS}}{\dot{Q}_{RAD}} \geq 1 \quad \text{when } T > 3\ keV$$

- $\dot{Q}_{TC}, \nabla T$ **must be approximated:**

$$\dot{Q}_{TC} \approx -\frac{1}{V}\int \nabla \bullet (K\nabla T) dV = -\frac{1}{V}\oint_S K\nabla T \bullet d\bar{S} \approx -\frac{S}{V} K \nabla T \approx \frac{KT}{\gamma \alpha \mathrm{a}^2}$$

$$\mathrm{a} = \text{characteristic dimension}, \quad V = \varepsilon \mathrm{a}^3, \quad \frac{V}{S} = \gamma \mathrm{a}, \quad \nabla T \approx -\frac{T}{\alpha \mathrm{a}}$$

- **ε,γ are geometric quantities, i.e., for spheres $\varepsilon=4\pi/3$, $\gamma=1/3$; simulations show $0.1 < \alpha < 0.5$; this paper uses $\alpha = 0.25$.**

- **a can be determined if the mass M is specified:** $\mathrm{a}^3 = \dfrac{M}{\varepsilon n_i (m_i + m_e)}$

The input energy & power required for hot spot gain G are set by the fuel pressure & β

$T = 10$ keV; p, β ➔ $n = p/(2kT)$
$\tau_E = G[n\tau_E]_L / n$ (Lawson)
$B = (2nkT/\beta)^{½}$

➔ Thermal diffusivity $\chi = f(n,T,B)$
e.g., $\chi_{Bohm} = kT/(16eB) \sim 1\ m^2/s$

➔ $R = (\chi\tau_E)^{½}$ & e.g., Volume $\propto R^3 \propto \tau_E^{1½} \propto p^{-1½}$

➔ Energy = 3nkT*Volume $\propto p^{-½}$
Power = Energy/$\tau_E \propto p^{½}$

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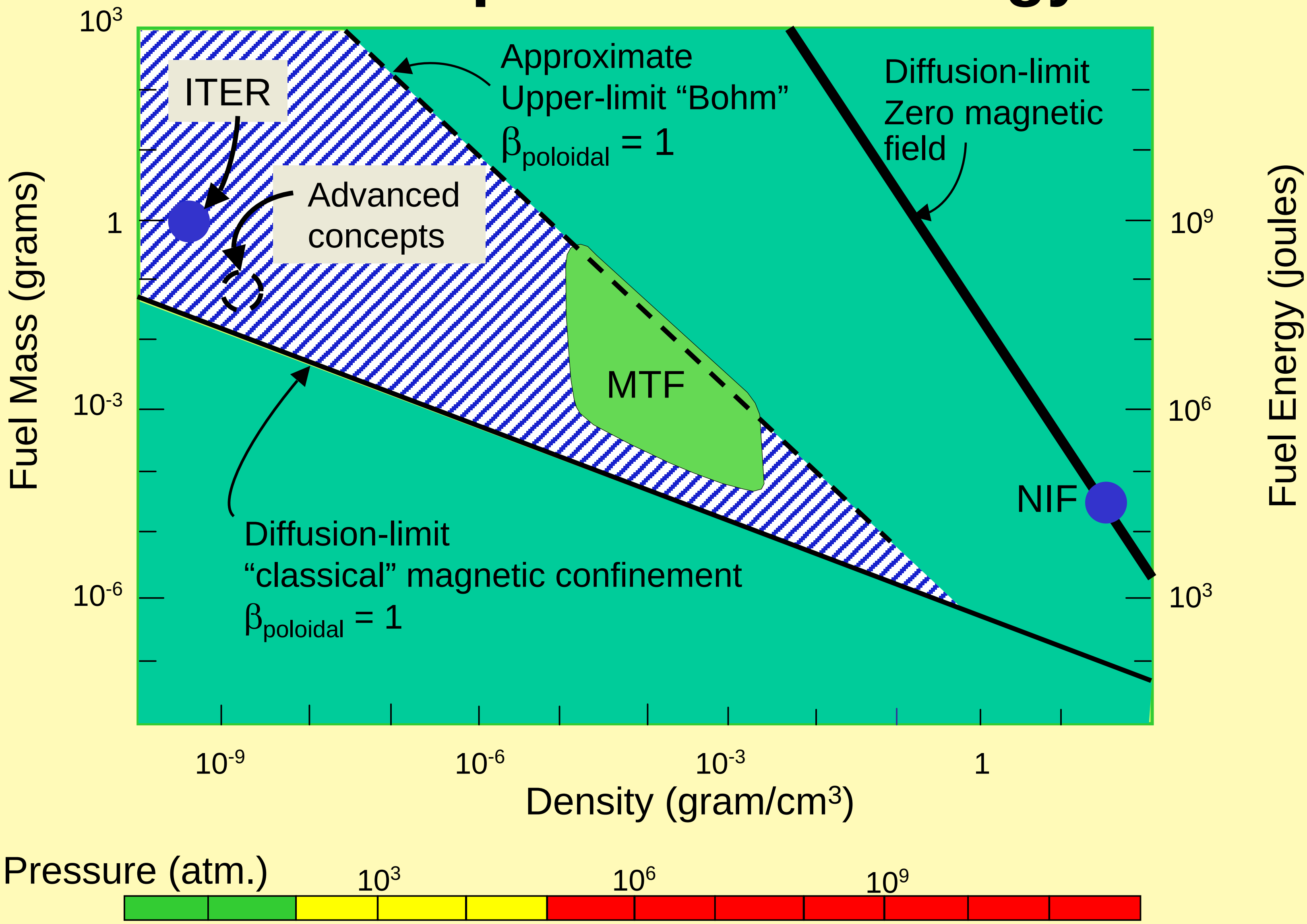
Thermal diffusion determines DT hot spot mass & energy



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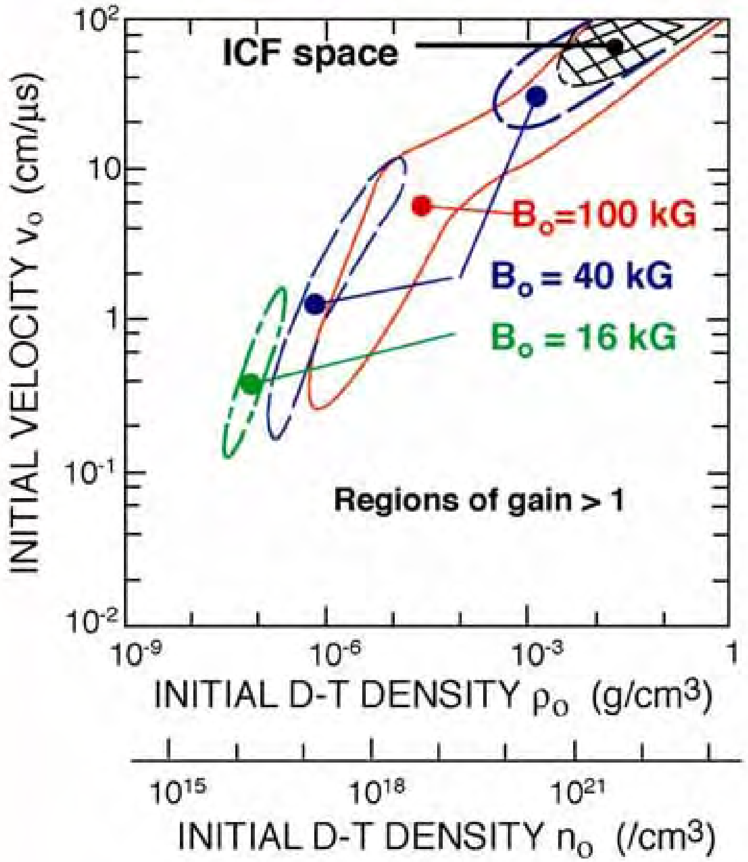
To fully determine the initial parameters (or final conditions), detailed implosion computations are needed.



- Lindemuth and Kirkpatrick (Nuc. Fus. 23, p. 263, 1983) formulated a simple implosion model and found a surprisingly broad parameter space.
- The results were confirmed by LASNEX and other computations.
- The simple model continues to serve as a guide for more detailed, multi-dimensional MHD computations.
- At the time the model was formulated, lasers were considered the most likely drivers, and plasma creation was considered a challenge (so use implosion E=10 kJ, T_o=50 eV).

The potential benefit of magnetic field in IFE

1. A) Magnetic thermal insulation could decrease the cost of a G~10 hot spot
   B) Alpha trapping can heat fuel with small ρr
2. What is magneto-inertial fusion (MIF)?
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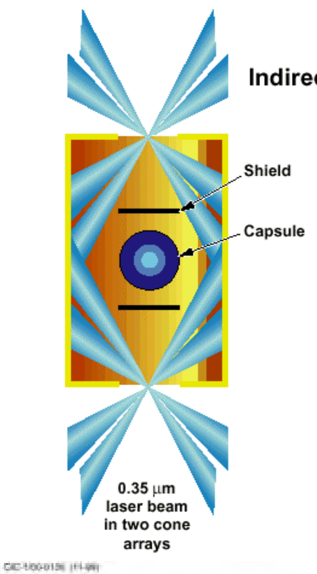
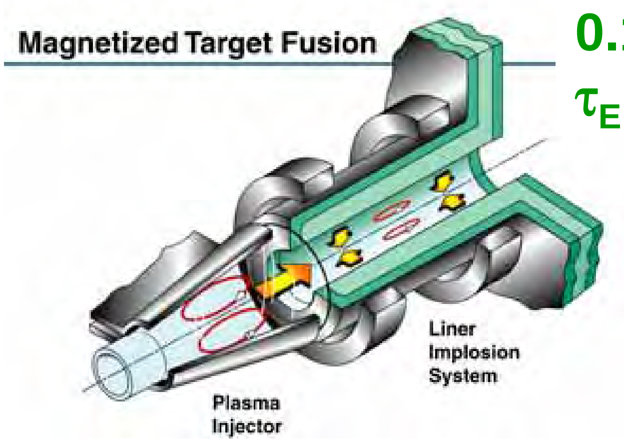
Magneto-inertial fusion: Dense fuel + magnetic insulation

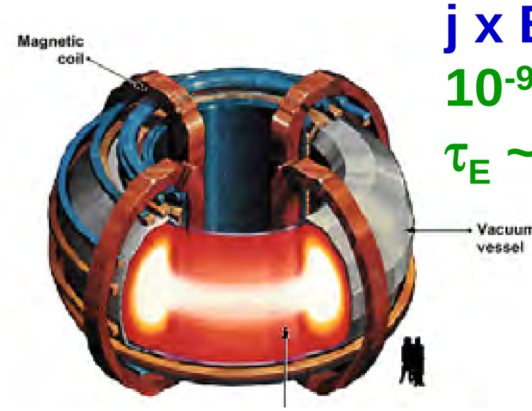


DT fuel:
100 gm/cm^3
e$^-$ thermal
conduction:
$\tau_E \sim 10$ ps

	Particle Confinement	Energy Confinement
ICF	Inertial	Inertial
MIF	Inertial	Magnetic
MFE	Magnetic	Magnetic

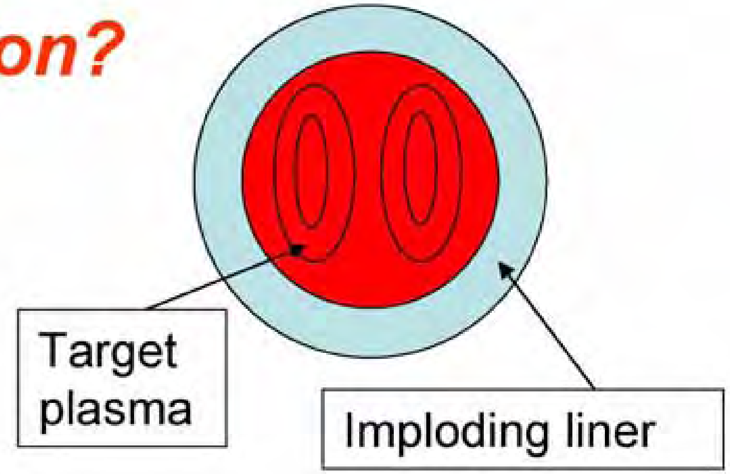


0.1 gm/cm^3
$\tau_E \sim 100$ ns



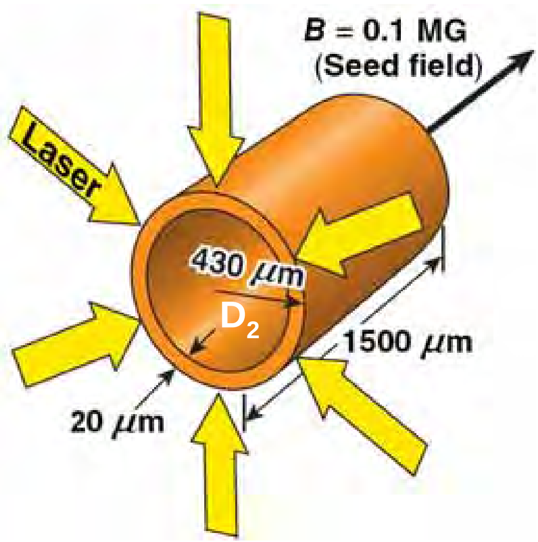
$j \times B = \nabla p$
10^{-9} gm/cm^3
$\tau_E \sim 1$ s

What is Magneto-Inertial Fusion?



- A method to make fusion energy, using a combination of magnetic and inertial techniques
- Uses a material shell (liner) to compress a plasma in which there is a seed magnetic field
- The liner is a magnetic flux conserver
  - The magnetic flux is conserved
  - Compression of the flux leads to increased magnetic field
- The magnetic field at peak compression is > 500 Tesla
  - The high B field suppresses cross-field thermal conduction
  - Relaxes the driver requirement
  - The high B field enhances deposition of alpha energy leading to bootstrapping of the fusion burn to obtain higher gain
- At peak compression, the fusing plasma has a pressure of ~ 1 Megabar or higher. A HEDLP approach to fusion.
- Combines knowledge of compact toroid plasmas (from MFE), with liner implosion technology (from DOD & NNSA)
  - Research can be conducted with existing facilities and technologies

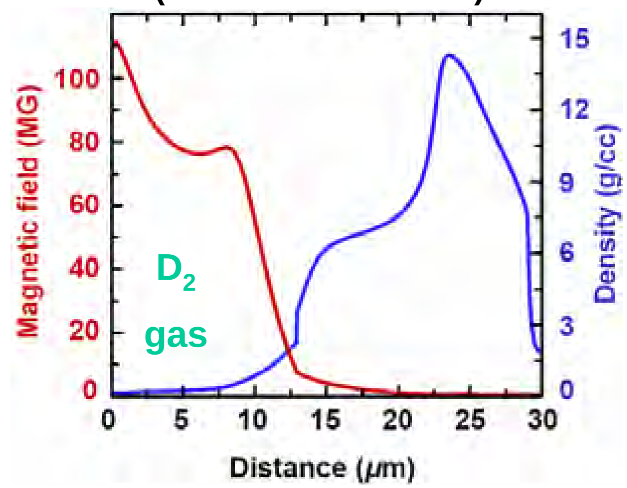
Magneto-inertial fusion experiments on the OMEGA laser will create MG fields for ICF hot spot insulation



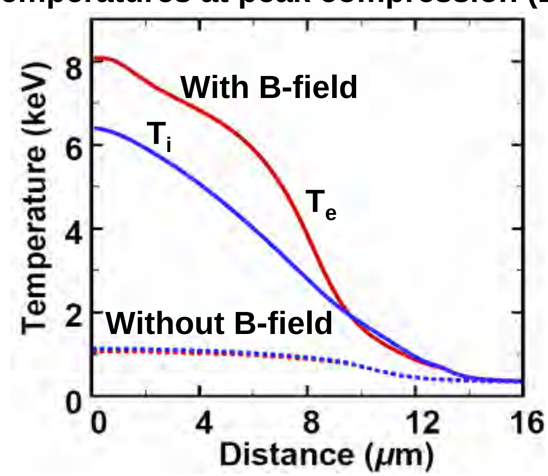
A cylindrical target filled with D_2 gas is imploded by OMEGA to compress a pre-seeded ~0.1 MG magnetic field to high values.

The compressed magnetic field inhibits the thermal transport, leading to increase of the hot spot temperature.

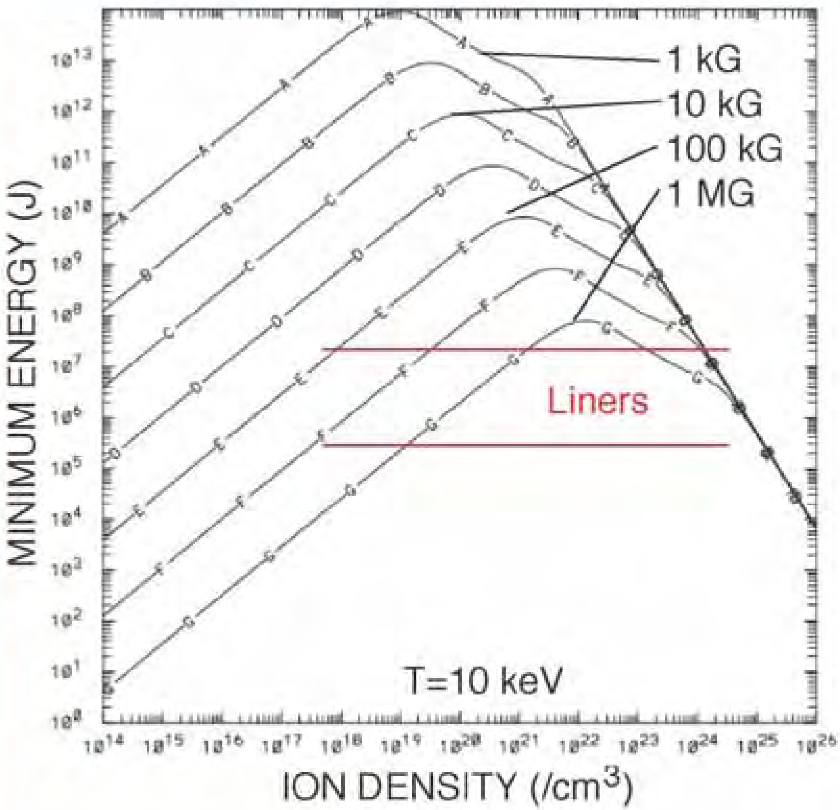
B-field at peak compression (1D MHD simulations)

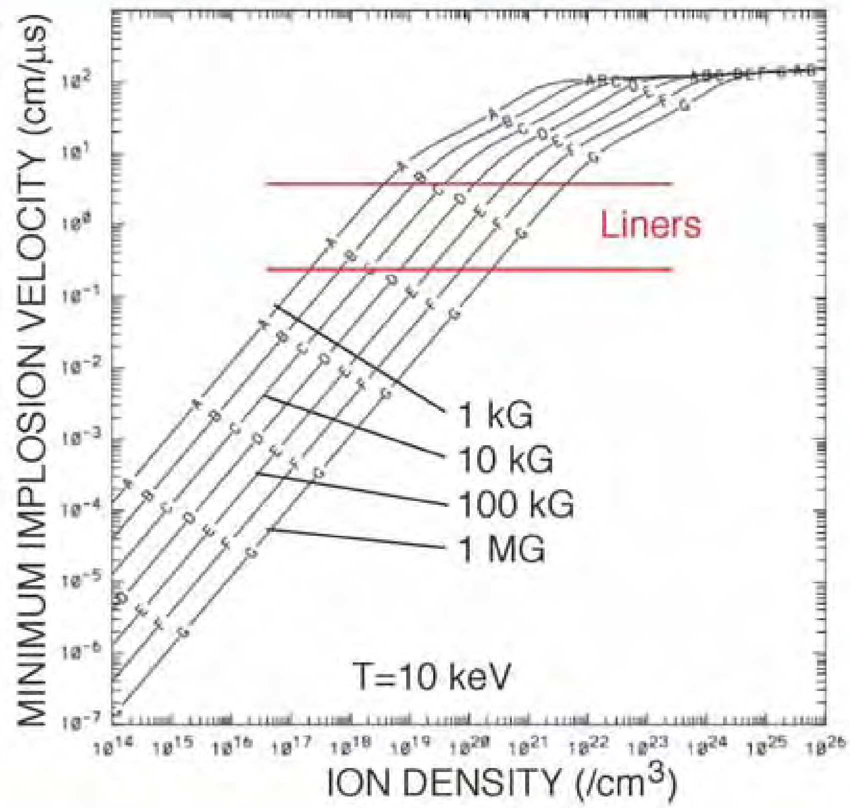


Temperatures at peak compression (1D)



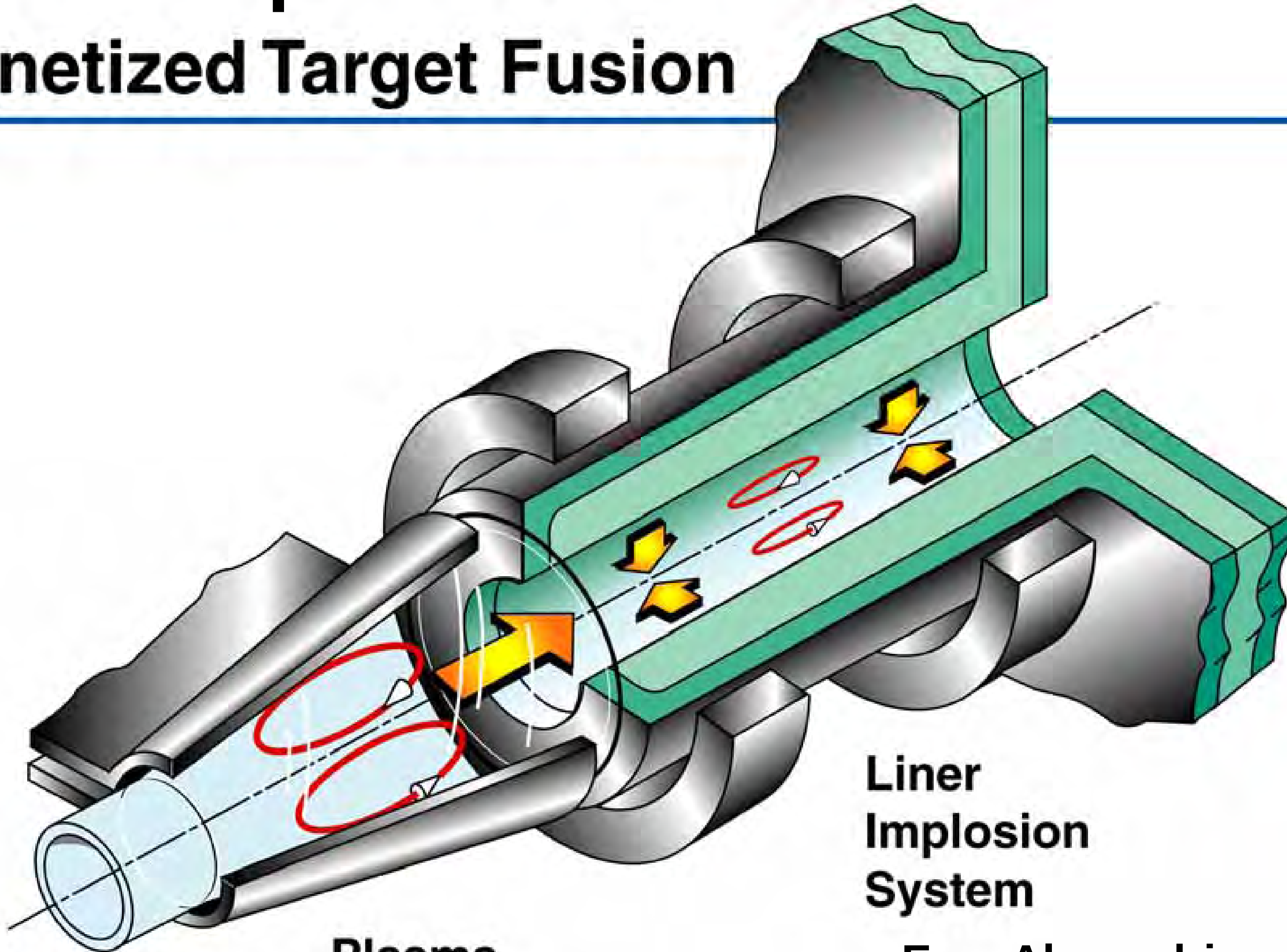
If very efficient compressional heating, as in ICF, is used to access the intermediate region, the required energy and implosion velocity is in the range already demonstrated by liners driven by modern high-current pulsed power machines (Atlas, Shiva-Star) and modern flux compression generators (DEMG).





One concept for MIF

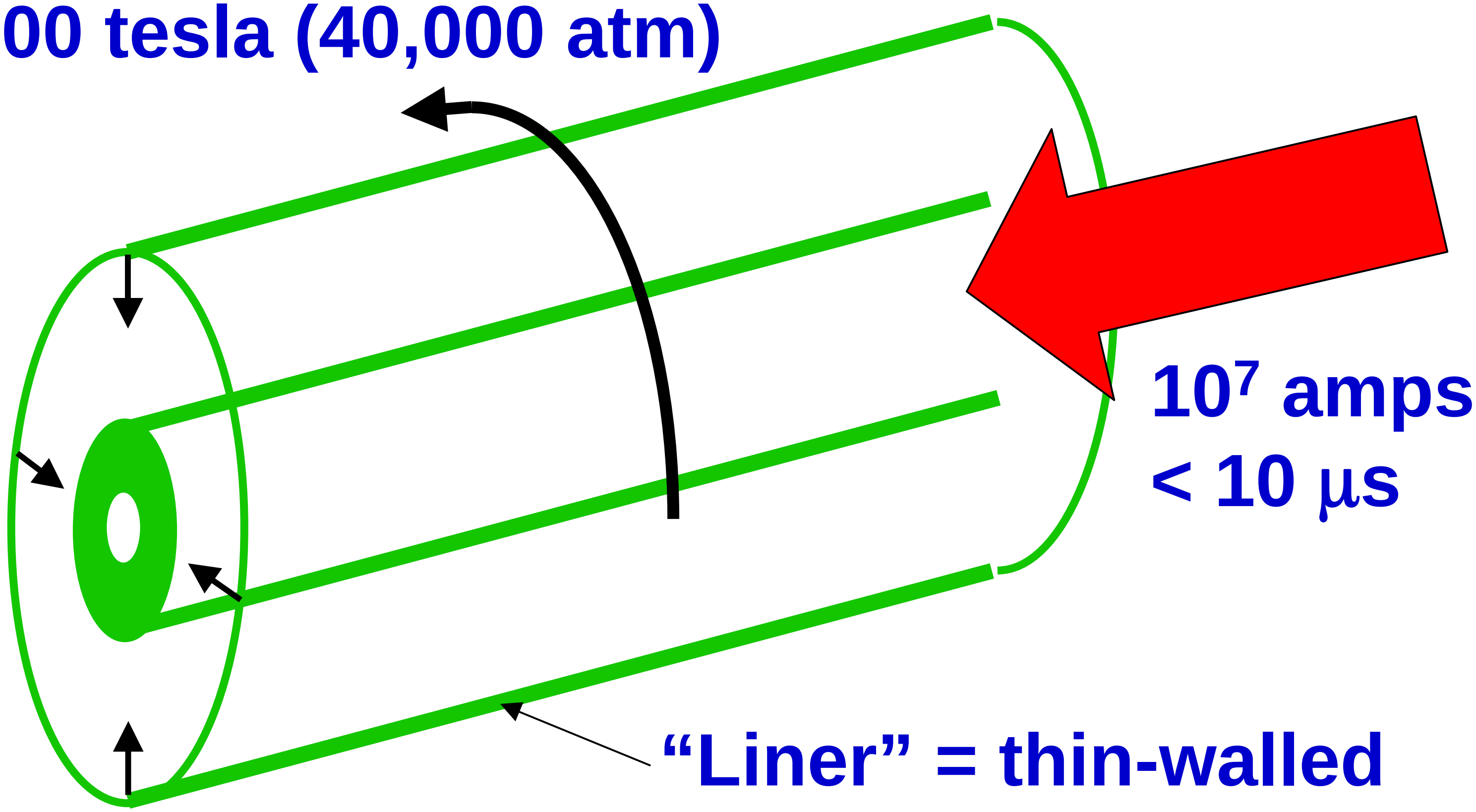
Magnetized Target Fusion



- E.g., Al can driven by $I > 1$ MA, $B_\theta \sim 100$ T

A large current compresses a liner

B_θ ~ 100 tesla (40,000 atm)



10^7 amps
< 10 μs

"Liner" = thin-walled aluminum cylinder the size of a beer can

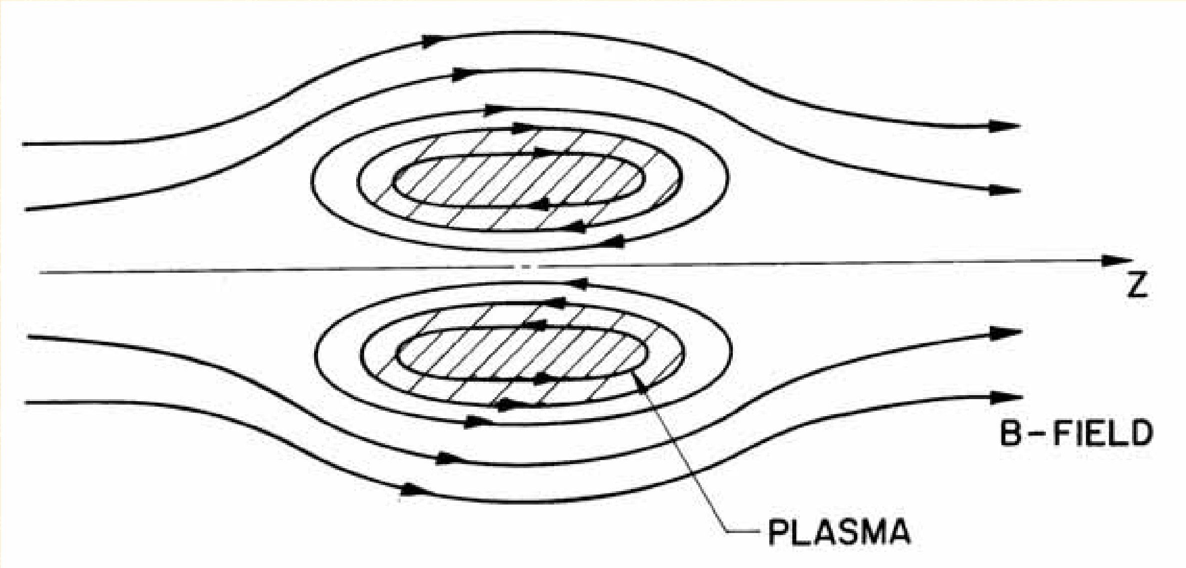
Low-cost electric pulsed power can apply plenty of pressure, energy, & power

- **Superconducting magnets (constant)**
  - **B < 15 Tesla**
  - **p < $\beta B^2/2\mu_0 \sim 100$ atm**

- **Liner technology (pulsed 10^7J / 10^{-5}s ~ 10^{12} W)**
  - **B ~ 10^3 Tesla**
  - **p ~ $\beta B^2/2\mu_0 \sim 10^6$ atm**

- **Laser compression (pulsed)**
  - **p ~ 10^{11} atm**

Field Reversed Configuration high-β self-organized plasma



- $\langle\beta\rangle \sim 1$
- compact torus like spheromak
- Can translate into liner

Main issue: Will liner compression generate high temperatures?

MIF could have advantages

- ✓ Low ρ → bigger, cheaper targets
- ✓ High To → reduced radial convergence (e.g., 10)
- ✓ Low v → less power, intensity
  → more & cheaper energy possible
- ✓ Low v, Bo → adiabatic compression
  → no pulse shaping, no shocks
- ✓ Big targets, low v → massive pushers
  → long dwell, burn times
- ✓ B → rB, not ρr, for alpha deposition

The potential benefit of magnetic field in IFE

1. A) Magnetic thermal insulation could decrease the cost of a G~10 hot spot
   B) Alpha trapping can heat fuel with small ρr
2. Magneto-inertial fusion (MIF)
   = Inertial particle confinement
   + Magnetic thermal insulation
3. Can MIF provide economical energy?
4. What research is underway?

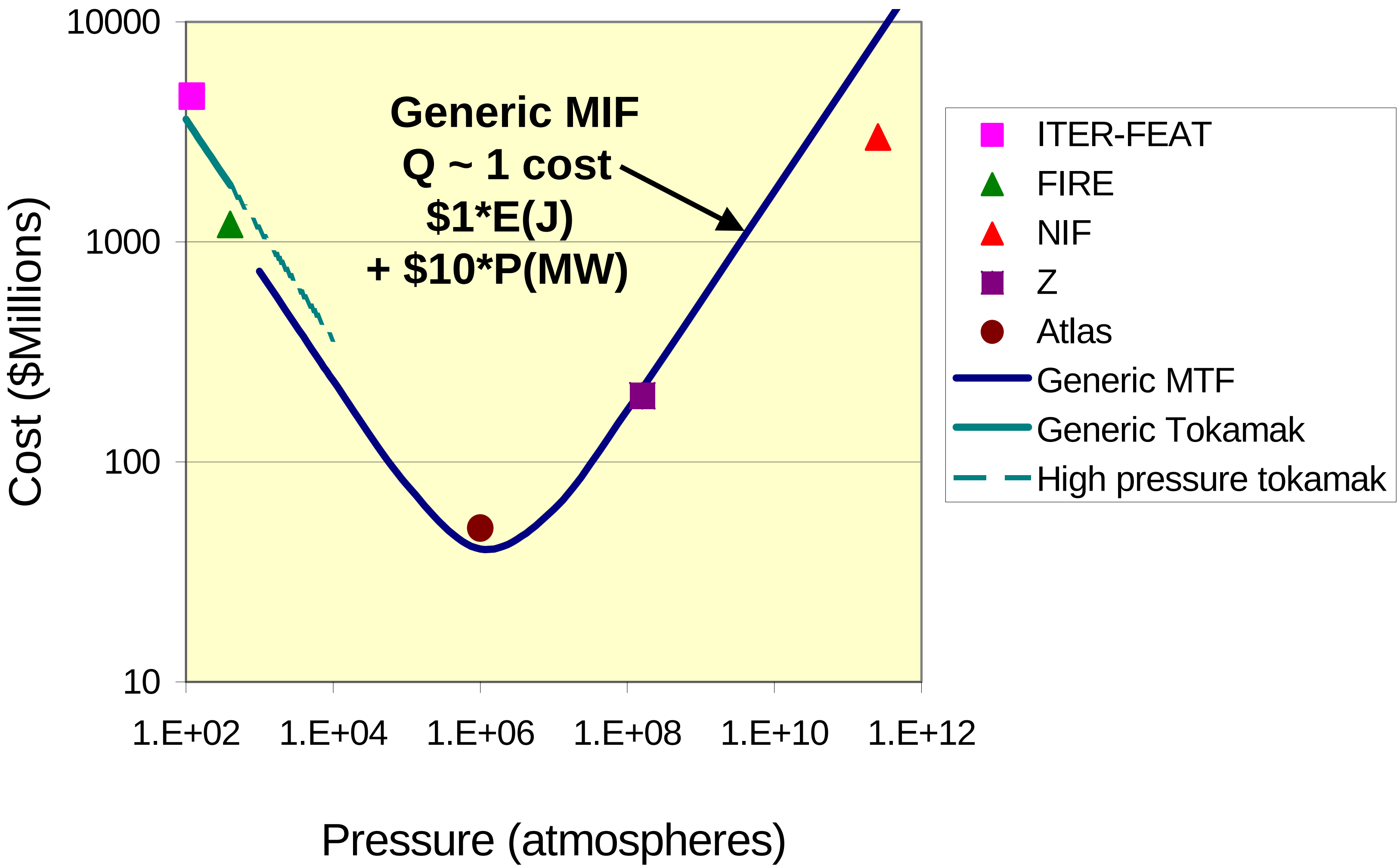
The “kopeck” problem

- Jim Tuck was one of the fusion energy pioneers at Los Alamos
- When first informed of laser fusion he scoffed
- He noted that the likely value of the energy pulse generated would best be reckoned in kopecks (= 0.01 Soviet Rubles) rather than dollars
- Not only must energy be produced, but the value of that energy must be more than the cost to produce it

MIF could solve the kopeck problem

- ✓ Cost-effective capacitor bank driver
- ✓ Efficiently heated G~10 hot spot
- ✓ Overall fusion gain could reach G~50 with edge fueling (by cool fuel at wall or jets)
- ✓ Non-cryogenic, macroscopic, simple target
- ✓ Driver stand off via recyclable transmission lines
- ✓ 10 GJ output ~ $50 of heat per shot

MIF seeks minimum-cost trade-off between input energy & power



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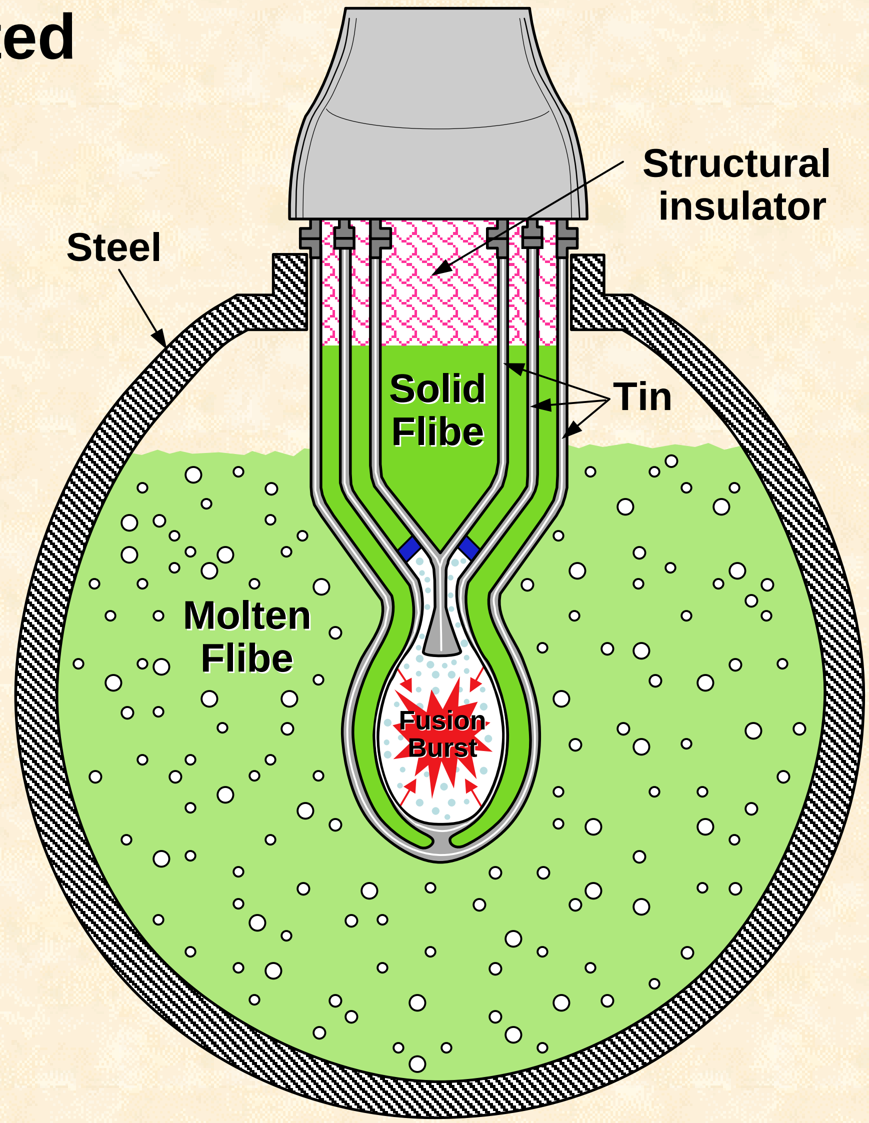
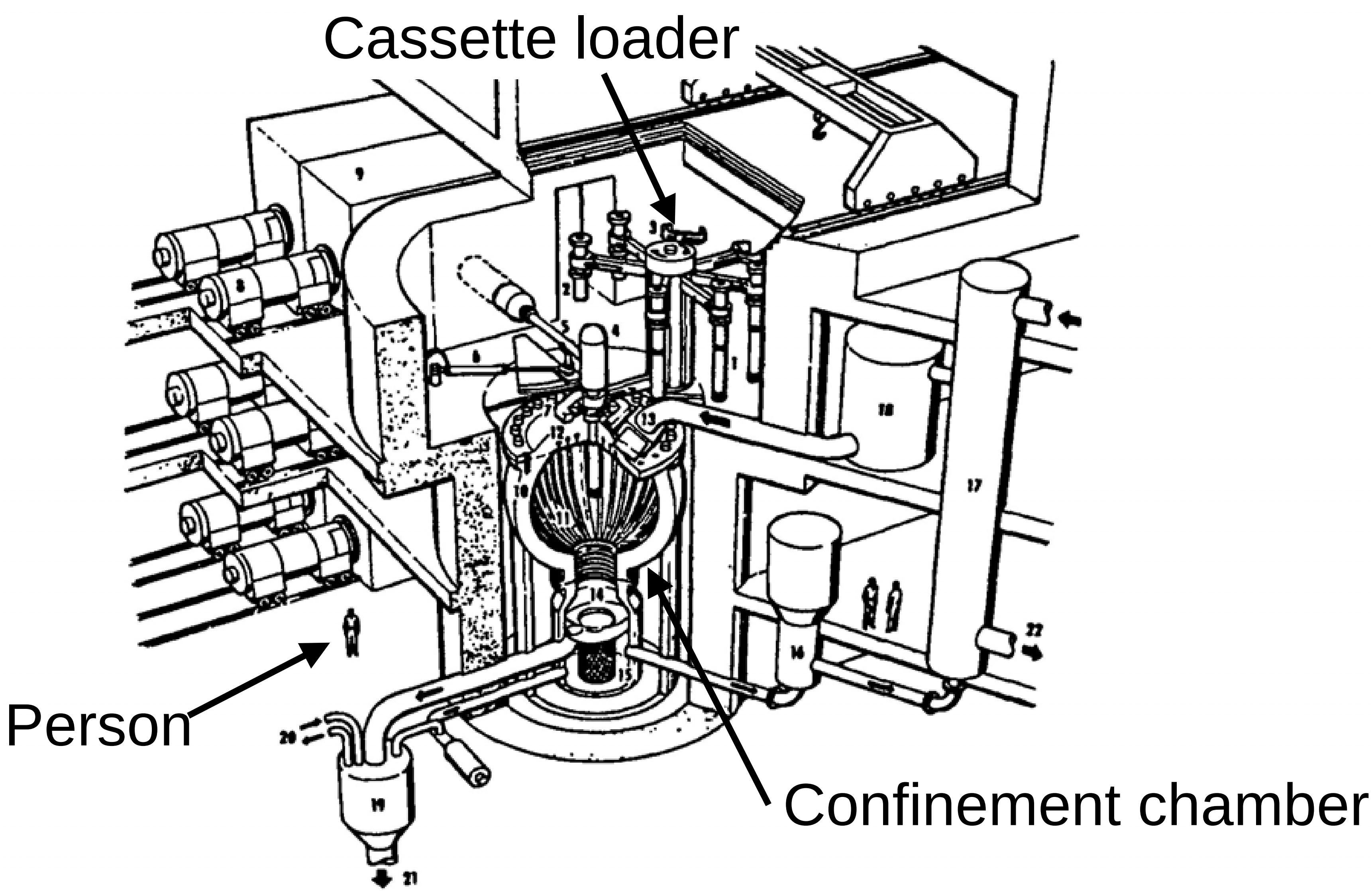
MIF might use Flibe working fluid

- Recycled tin flibe-insulated transmission lines
- Flibe primary coolant at 550 ^{o}C (T_{melt} = 459 ^{o}C)
- Tin T_{melt} = 232 ^{o}C inserted short time
- Studied by P. Peterson, UC Berkeley

Note – no line of sight needed; electricity goes around corners



MTF power plant concept



The potential benefit of magnetic field in IFE

1. A) Magnetic thermal insulation could decrease the cost of a G~10 hot spot
   B) Alpha trapping can heat fuel with small ρr

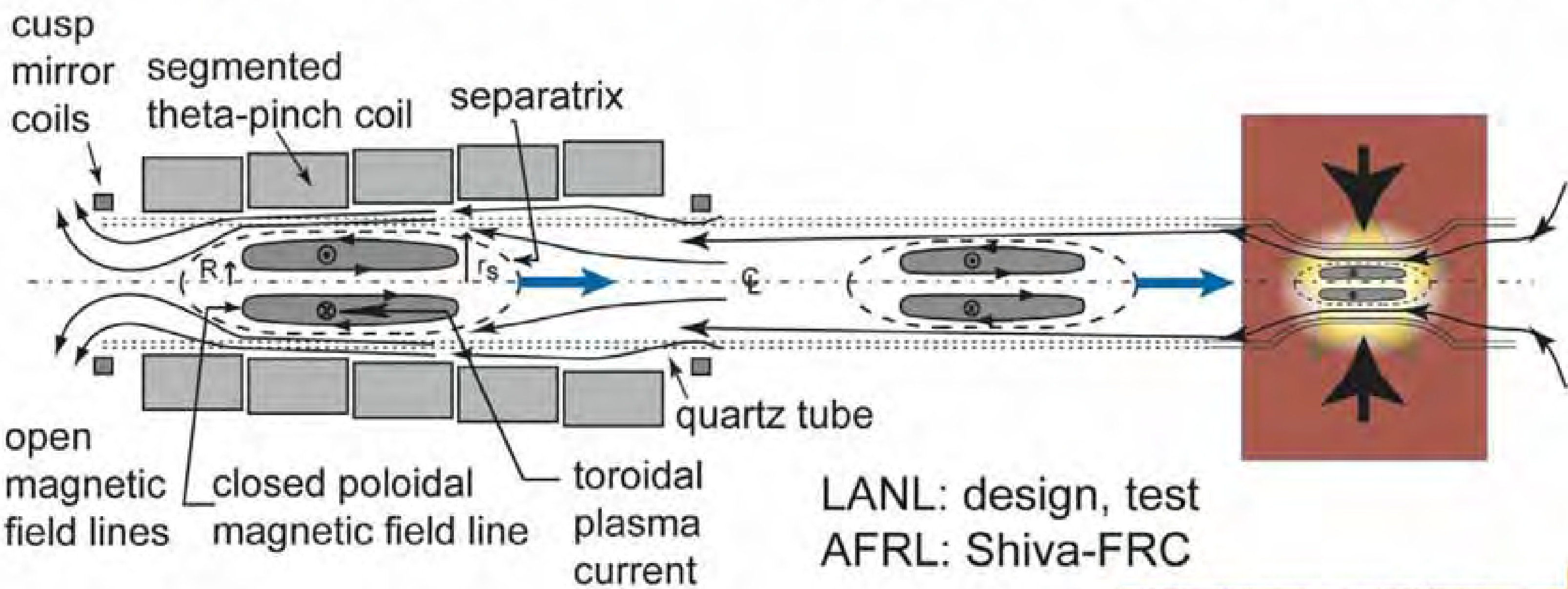
2. Magneto-inertial fusion (MIF)
   = Inertial particle confinement
   + Magnetic thermal insulation

3. A simple driver & target could yield enough energy per shot (10 GJ) to be profitable

4. What research is underway?

Solid-Liner Driven Magneto-Inertial Fusion
FY2008….first physics demonstration of MIF

Formation: LANL Translation Compression

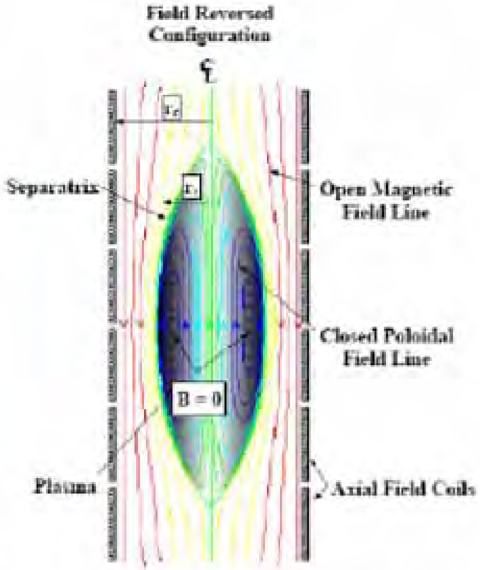


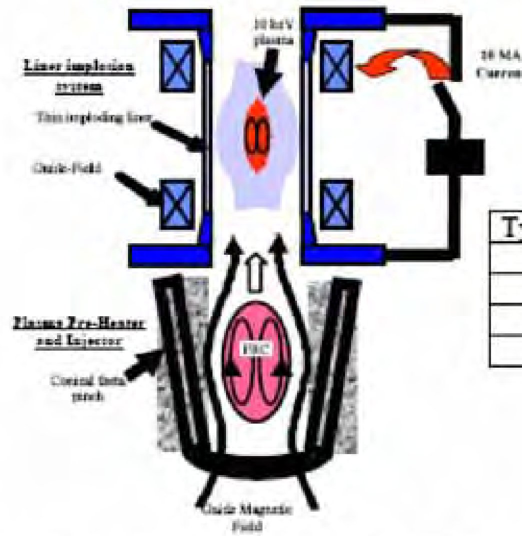
LANL: design, test
AFRL: Shiva-FRC

- Pulsed, high pressure approach to fusion
- Inertial + magnetic confinement
- Multi-keV fusion grade plasma

$2.2M in FY 2007

Current Status





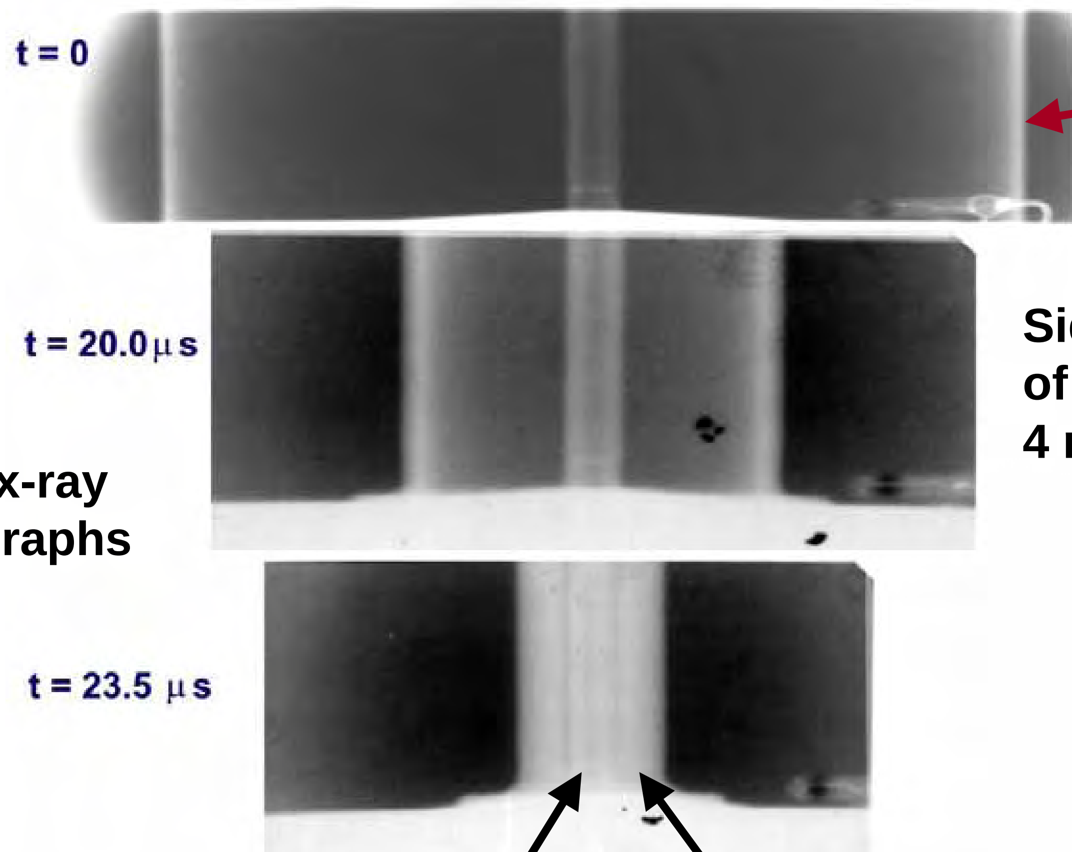
Typical parameters:		
	Initial	Final
n	~10^{17} cm^{-3}	~10^{19} cm^{-3}
T	~200 eV	~5 keV
B	~5 T	~500 T

• Small, compact FRC formed with high density (~5 x 10^16 ion/cc), temperature > 200 eV with radii ~ 2 cm, suitable for implosion experiment. Historical FRC's are much lower density, larger size.

• Imploding liner experiments achieve suitable implosion features for FRC injection and compression to MTF conditions (size, velocity, symmetry, lack of instability growth, radial convergence, and sufficiently large electrode apertures)

•2D-MHD simulations of FRC formation, translation., and compression indicate potential for compressing magnetized plasmas to density ~ 10^19 ions/cc, T ~ 5 KeV, n-tau ~ 10^12 – 10^13 sec/cc

AFRL radiographs of liner implosion demonstrate good liner performance



Initial 1-mm thick Aluminum liner

Side-on view of liner moving 4 mm/μs

Flash x-ray radiographs

Stationary 6-mm probe jacket

Elastic-plastic deformed 7-mm thick liner at 12:1 radial compression

Courtesy of J. Degnan, AFRL

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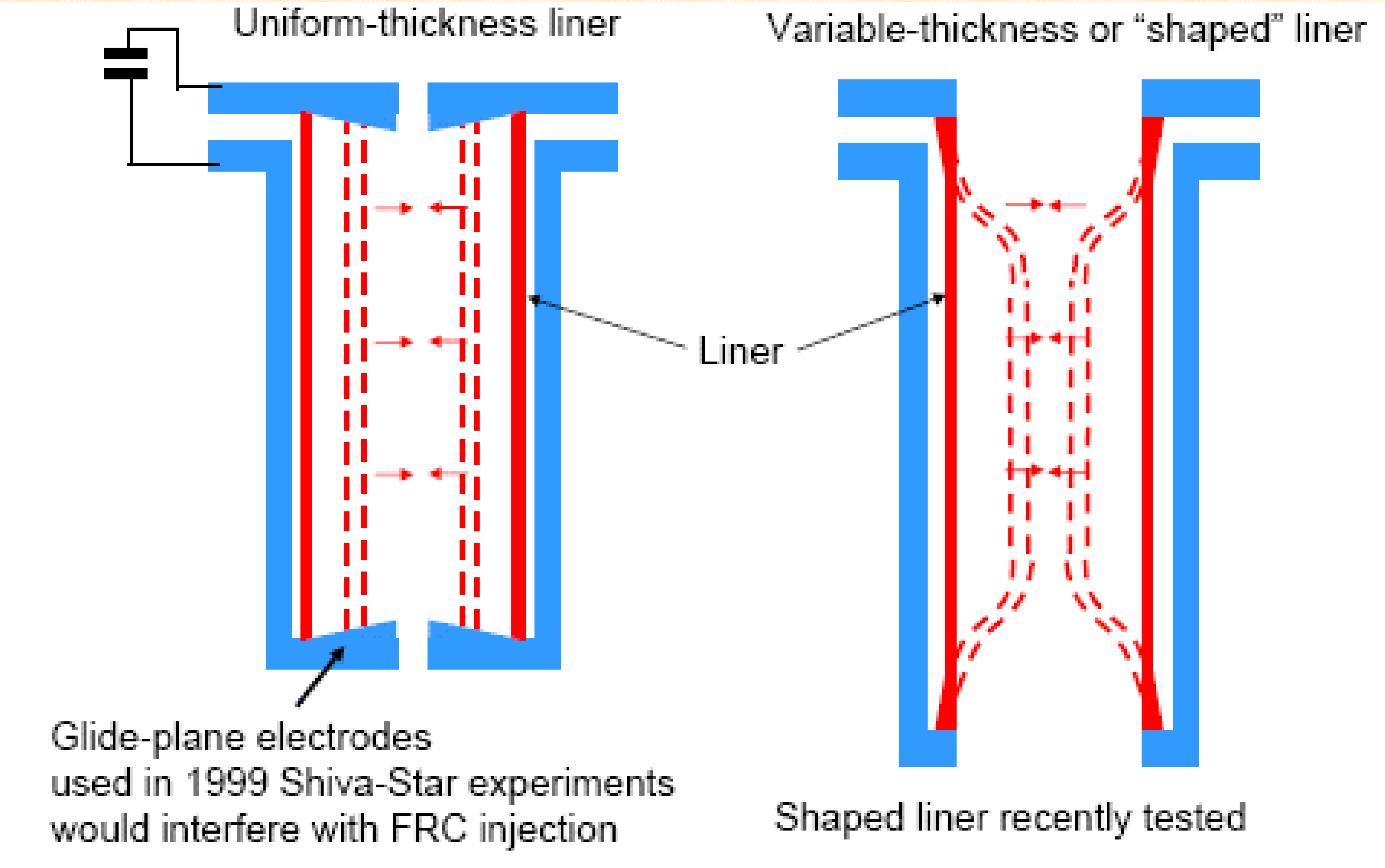
Glide planes interfere with FRC injection

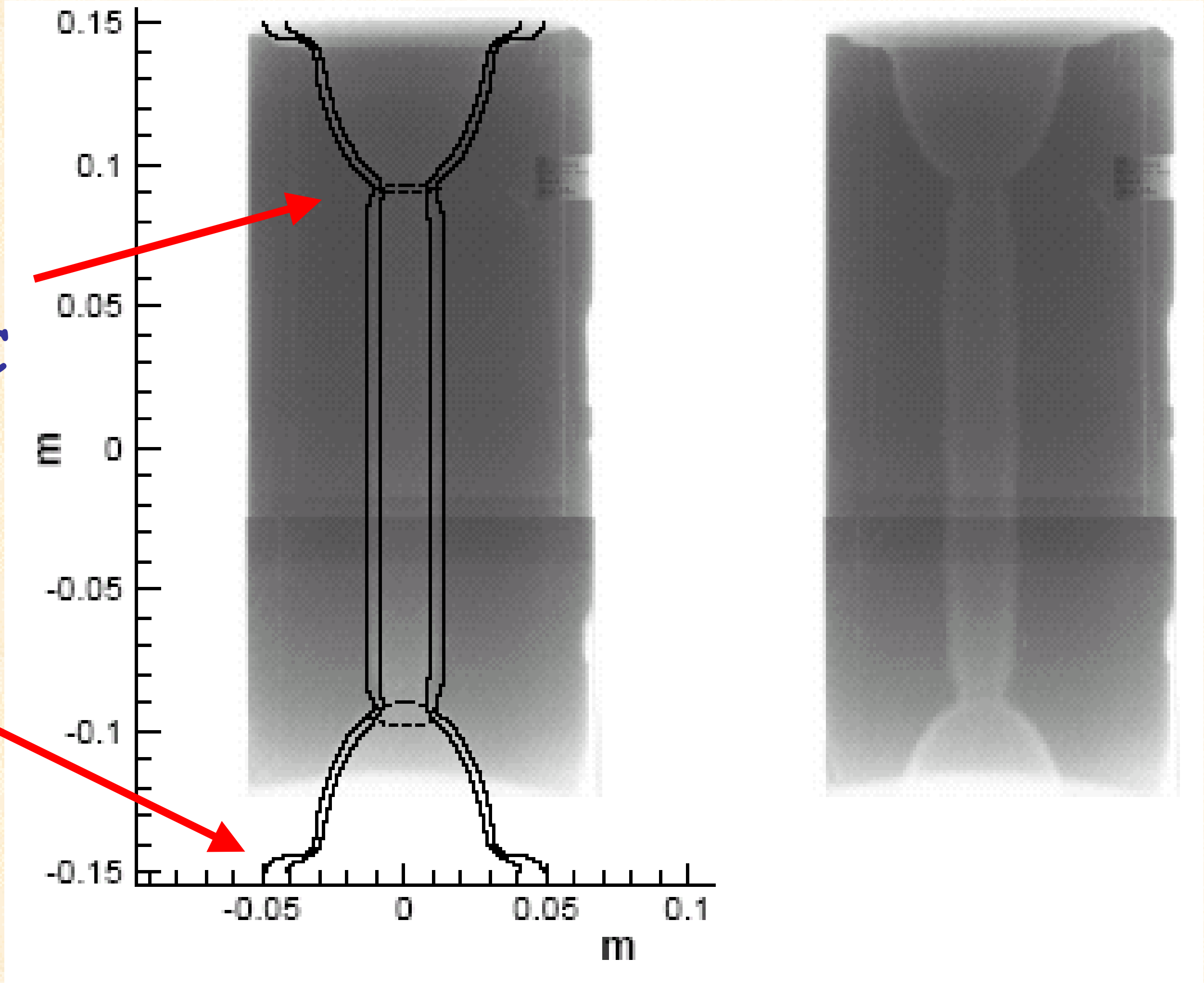


AFRL success with shaped liner

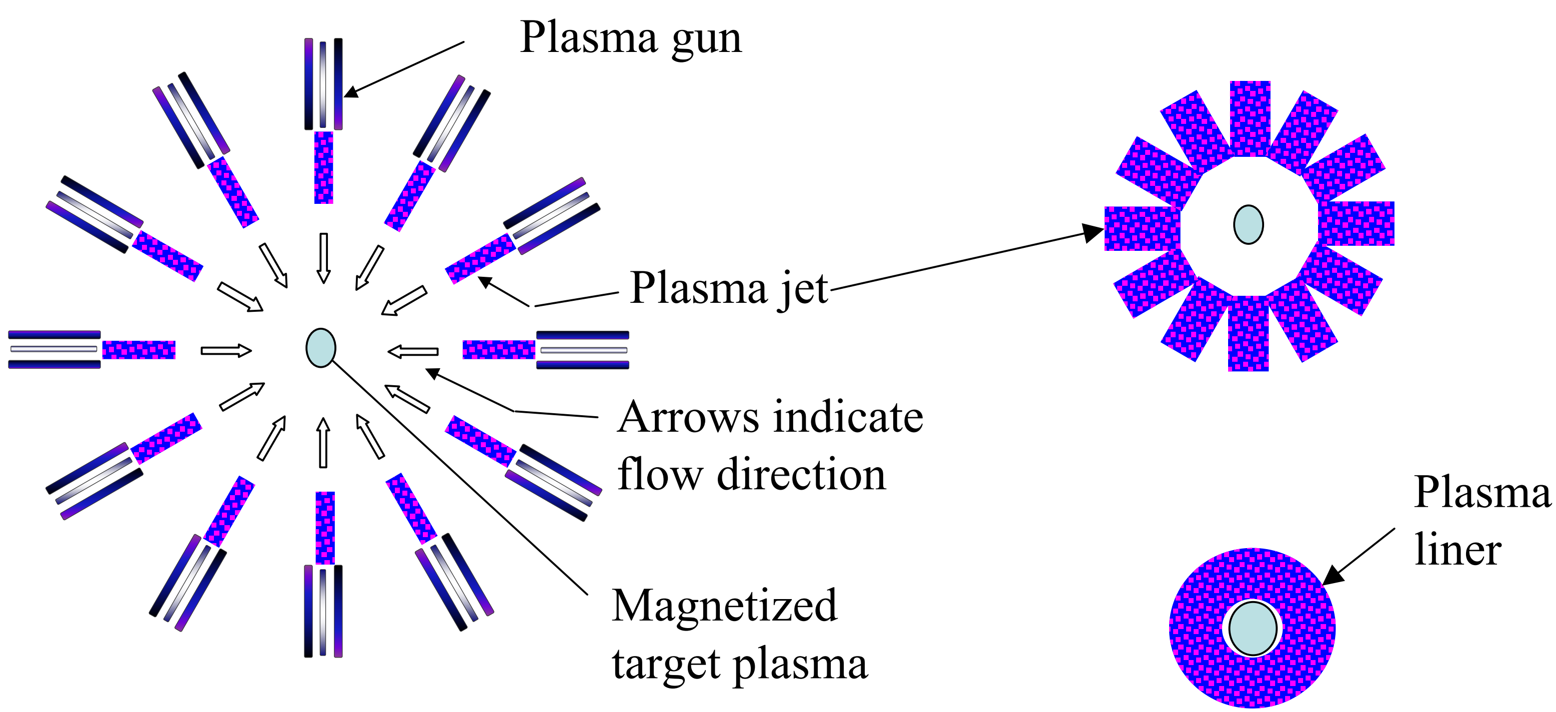
Radiograph plus simulation Radiograph alone

Enhanced magnetic mirror centers FRC

Glide planes eliminated



Implosions of high Mach number plasma jets has additional potential for fusion applications



- An approximately spherical distribution of jets are launched towards a common center
- The jets merge to form a spheroidal shell (liner), imploding towards the center

Plasma liners could be advantageous

- ✓ Standoff delivery of imploding momentum
- ✓ Inexpensive liner fabrication
- ✓ Repetitive operation
- ✓ Fast compression
- ✓ Possible remote current drive by lasers or particle beams
- ✓ Diagnostics could view both the liner and the target plasma
- ✓ Additional fuel for fusion

Supersonic Plasma Jets and Precursor Flows in Wire-Array Z-Pinch

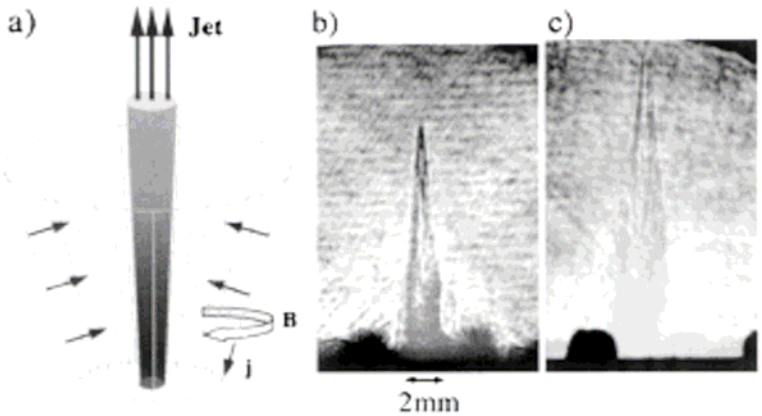


FIG. 1. (a) Diagram of jet formation in conical wire arrays, (b) Laser schlieren image of tungsten plasma jet after launch at 313 ns, and (c) at 343 ns.

J. P. Chittenden, et. al., “Indirect-Drive ICF using Supersonic, Radiatively Cooled, Plasma Slugs,” PRL, 88 (23), 2002

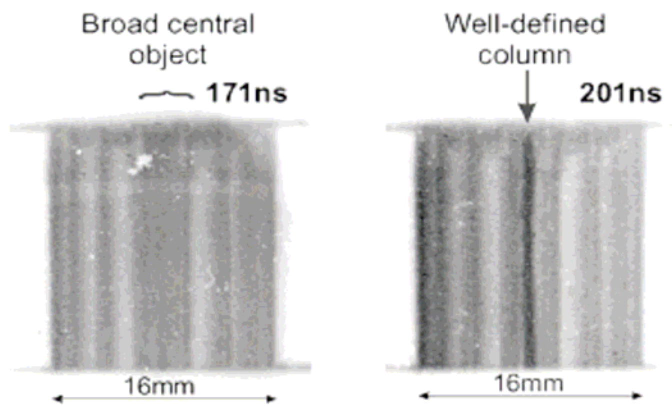


FIG. 2. Side on XUV emission image of a 16 wire tungsten array showing formation of the compact precursor column.

Cylindrically converging precursor plasma flow in wire-array Z-pinch Experiments.

S. C. Bott, et. al, Phys Rev E, 74, 2006.

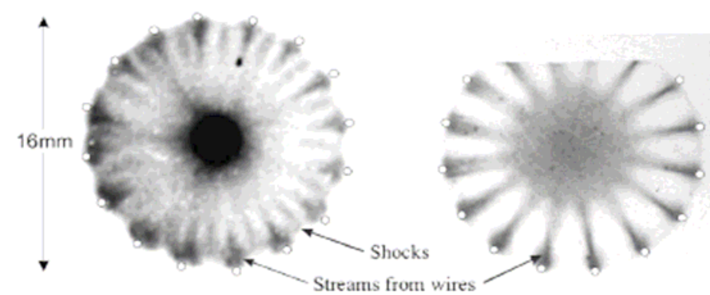
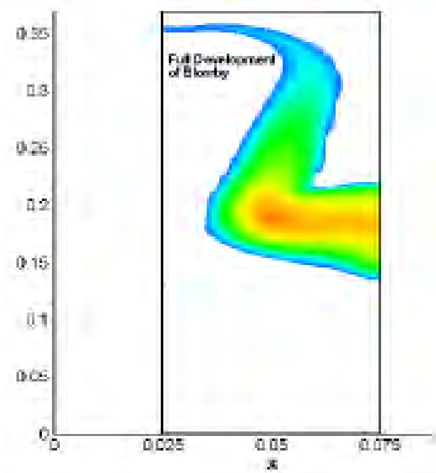
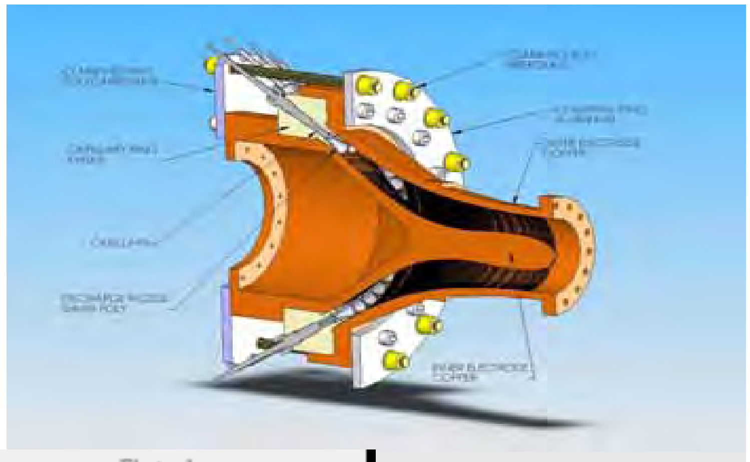
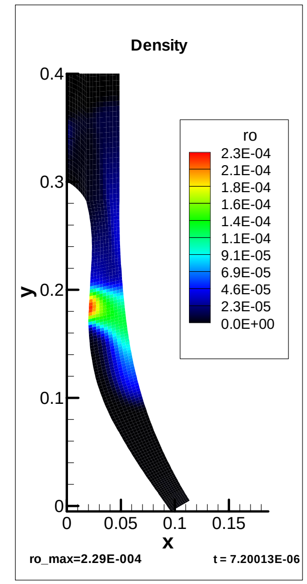


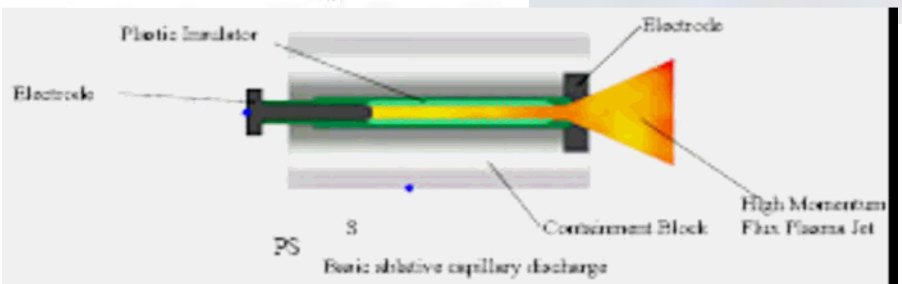
FIG. 3. End-on XUV emission from 16 mm diameter arrays of (left) 16×20 μm Al at 134 ns, and (right) 16×13 μm W at 134 ns. (White circles indicate positions of wires).

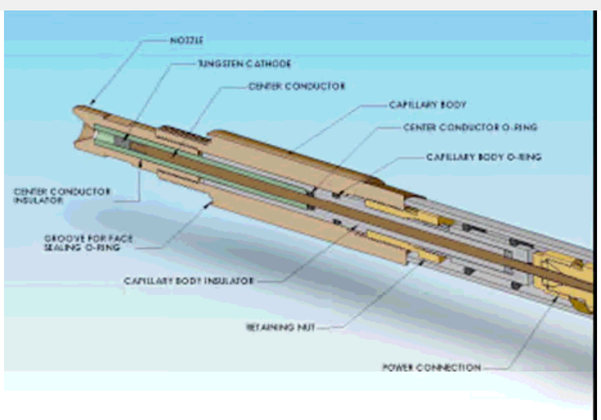
Development of High Mach Number Plasma Jets at HyperV Technologies

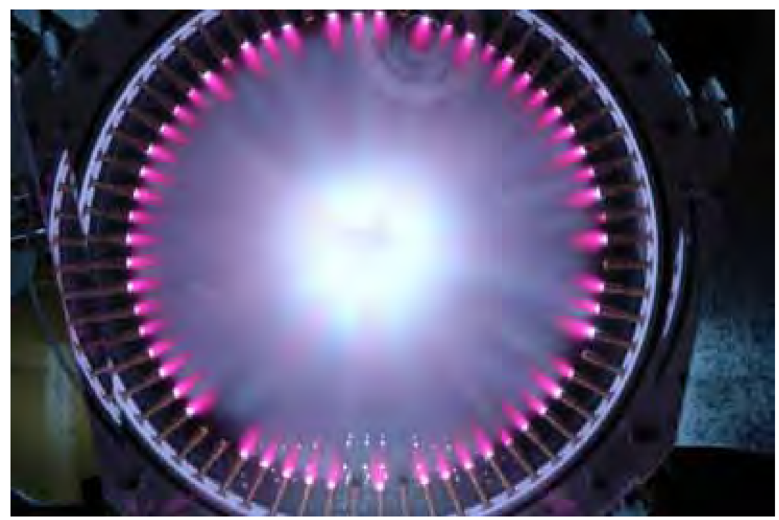




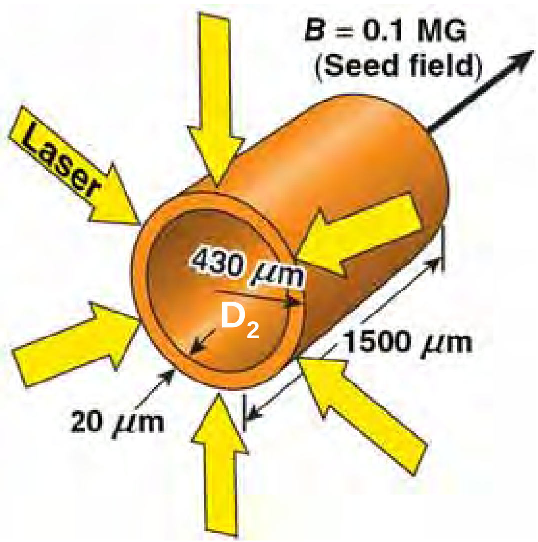




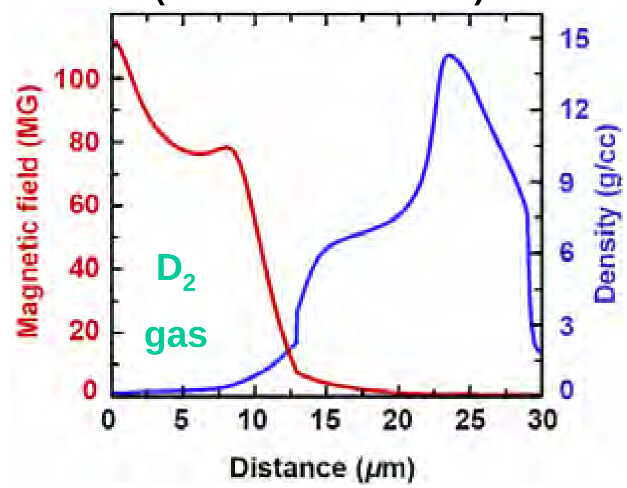




Magneto-inertial fusion experiments on the OMEGA laser will create MG fields for ICF hot spot insulation



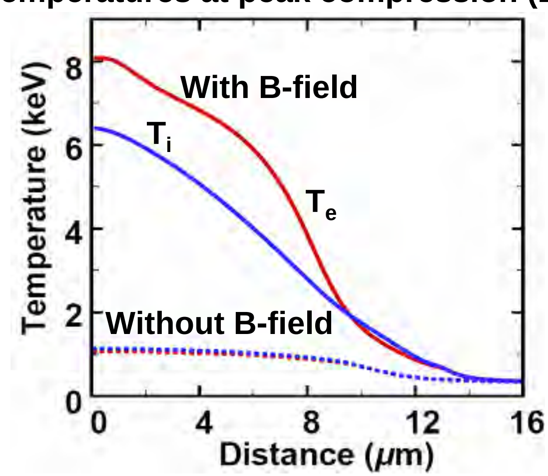
B-field at peak compression
(1D MHD simulations)



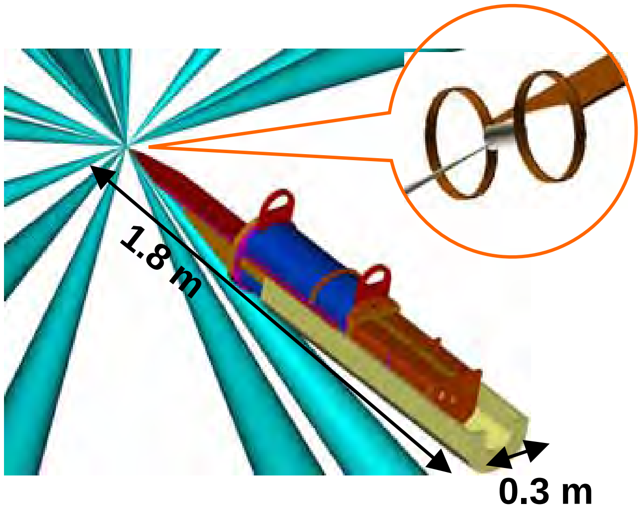
A cylindrical target filled with D_2 gas is imploded by OMEGA to compress a pre-seeded ~0.1 MG magnetic field to high values.

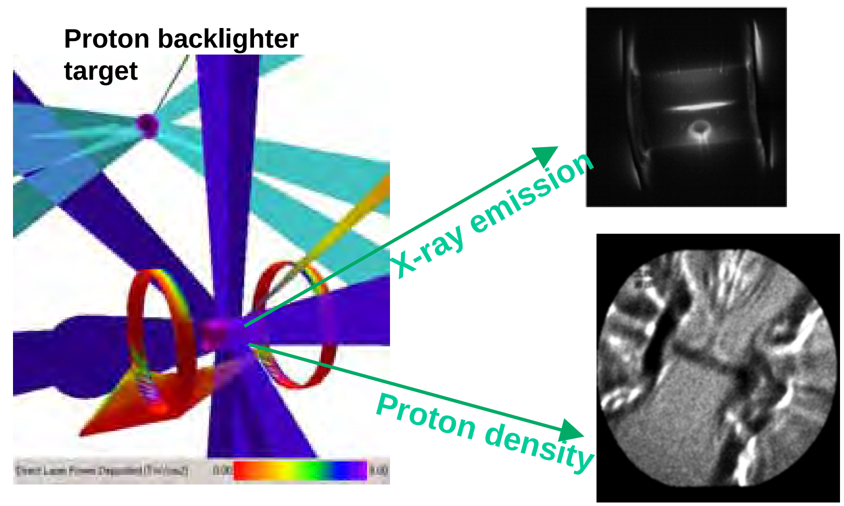
The compressed magnetic field inhibits the thermal transport, leading to increase of the hot spot temperature.

Temperatures at peak compression (1D)



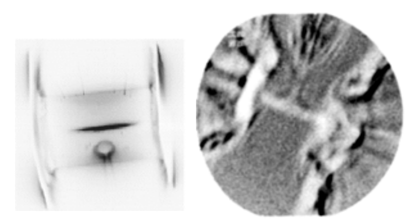
The seed magnetic field is generated in a double coil configuration suitable for OMEGA implosions





Proton deflectrometry technique was developed for detection of the compressed magnetic fields

The 400-ns, 0.1-MG seed magnetic pulse is generated by a compact, 100 Joule device delivering ~80 kA peak coil current.



Experiment on 1-MA Zebra (UNR) studies plasma formed by multi-MG field on aluminum

Please see poster by Bauer

The potential benefit of magnetic field in IFE

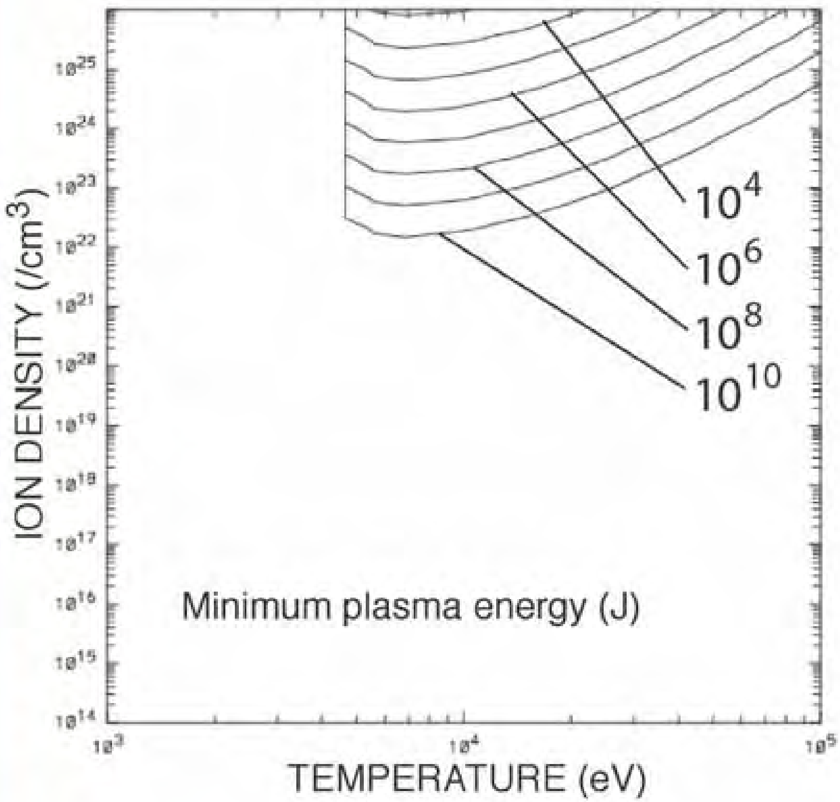
1. A) Magnetic thermal insulation could decrease the cost of a G~10 hot spot
   B) Alpha trapping can heat fuel with small ρr
2. Magneto-inertial fusion (MIF)
   = Inertial particle confinement
   + Magnetic thermal insulation
3. A simple driver & target could yield enough energy per shot (10 GJ) to be profitable
4. A variety of experiments will test MIF concepts in the HED regime

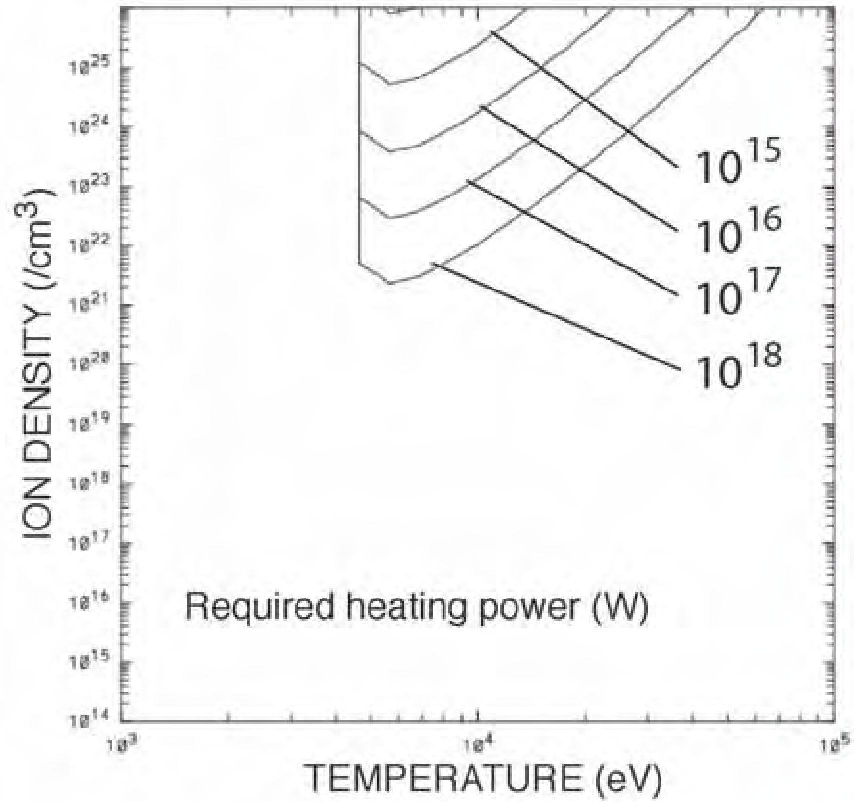
MIF faces IFE scientific and fusion reactor challenges

- High-energy-density physics
- Radiation-(magneto)hydrodynamics
- Rayleigh-Taylor instability
- Pulsed operation
- Driver stand off
- First-wall damage
- The kopeck problem

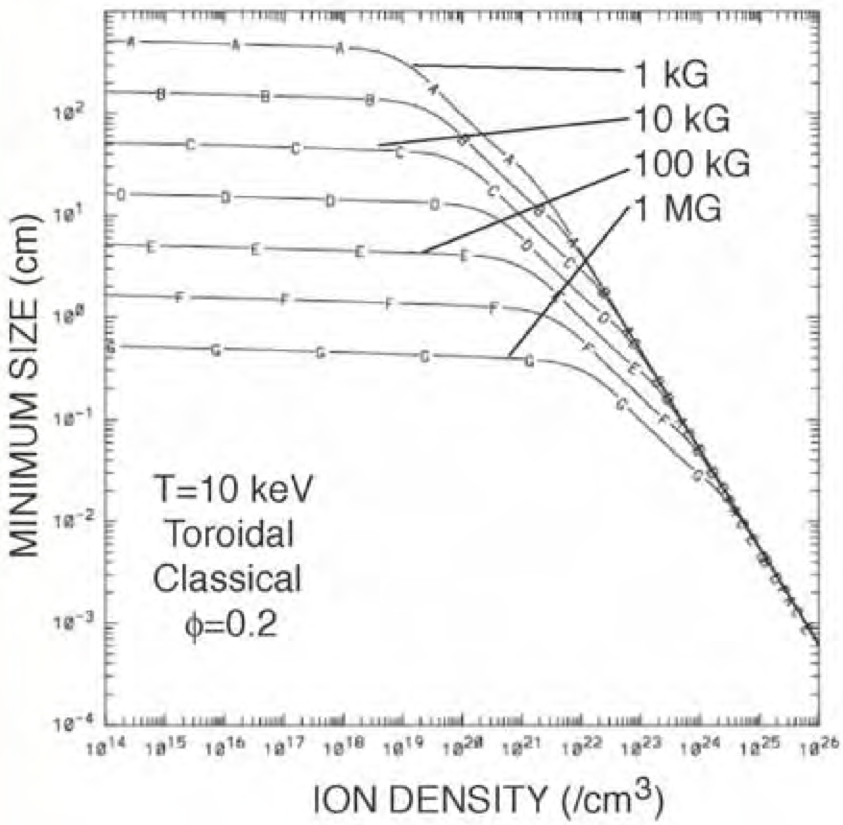
Thank you!

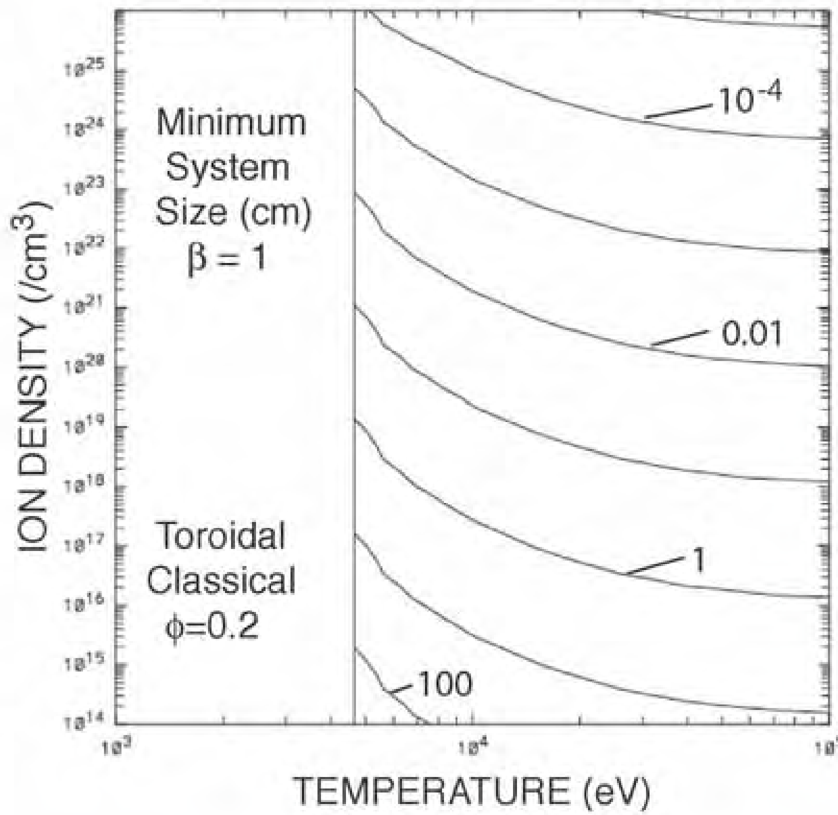
The high energy and high power requirements of unmagnetized (B=0) fuel forces NIF to operate at high-density.





A magnetic field can significantly reduce the size of the burning plasma.





Note: β=plasma pressure/magnetic pressure

MIF typically seeks B > 1 MG

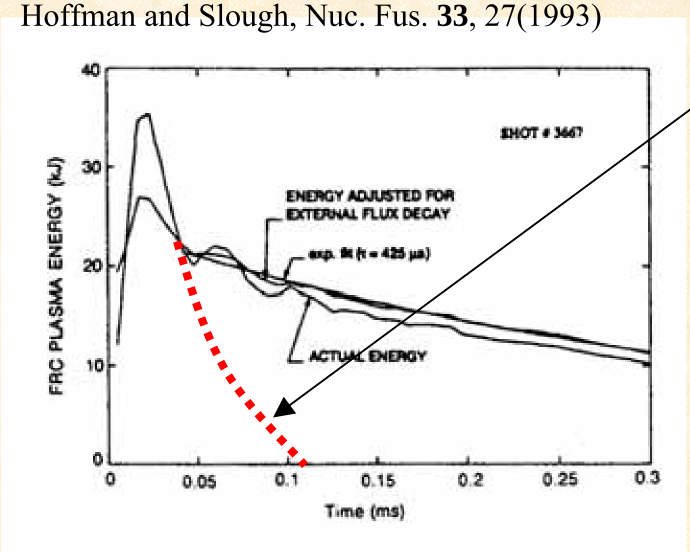
- An established method of generating MG fields is with metal liner implosions, often aluminum.
- Seed field is introduced into a cylindrical enclosure, which is then imploded by z pinch or theta pinch compression.
- Megagauss conferences have documented this possibility for more than 30 years

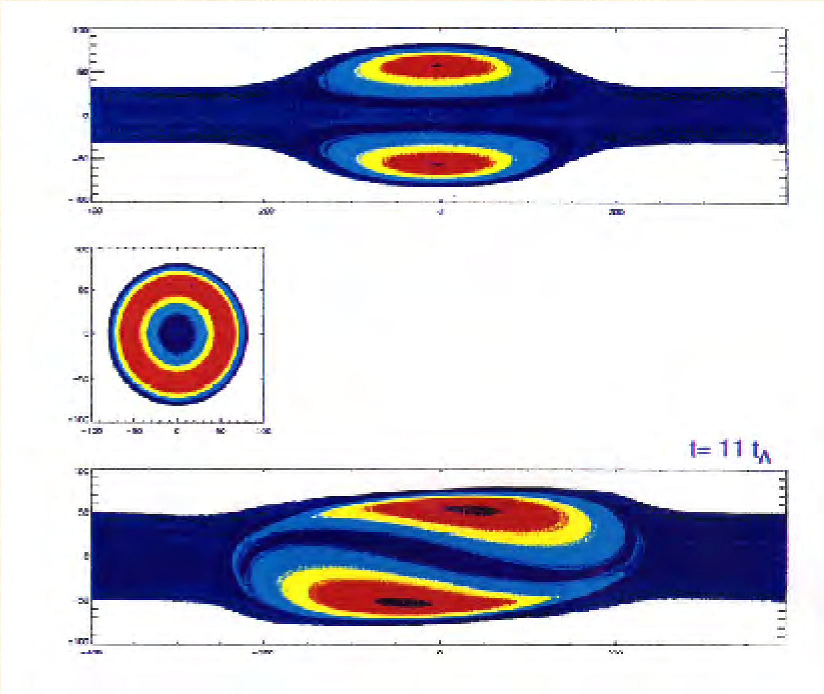
Theory of FRC behavior is incomplete

Experiments show slow decay

MHD theory predicts fast decay

Hoffman and Slough, Nuc. Fus. **33**, 27(1993)

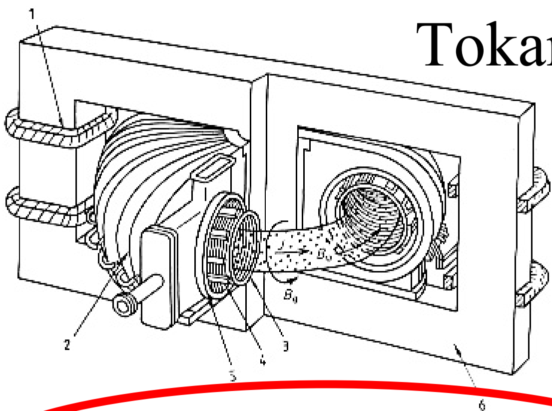




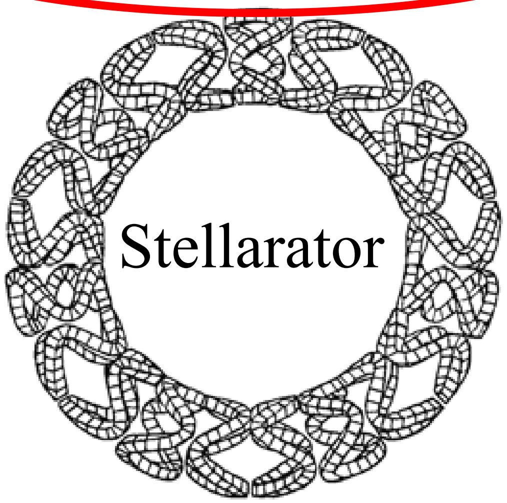
Recent theory suggests elongated shape can be stable
(D. C. Barnes, Phys. Plasmas, 2002)

Magnetic confinement: $j \times B = \nabla p$

Tokamaks

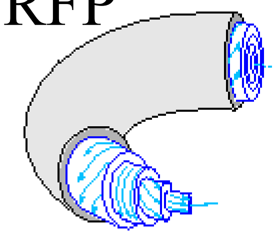


Externally controlled

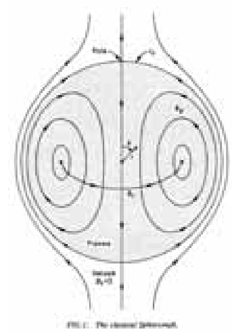


Stellarator

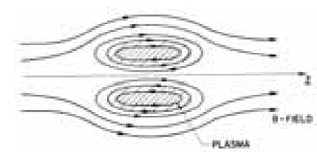
RFP



Spheromak



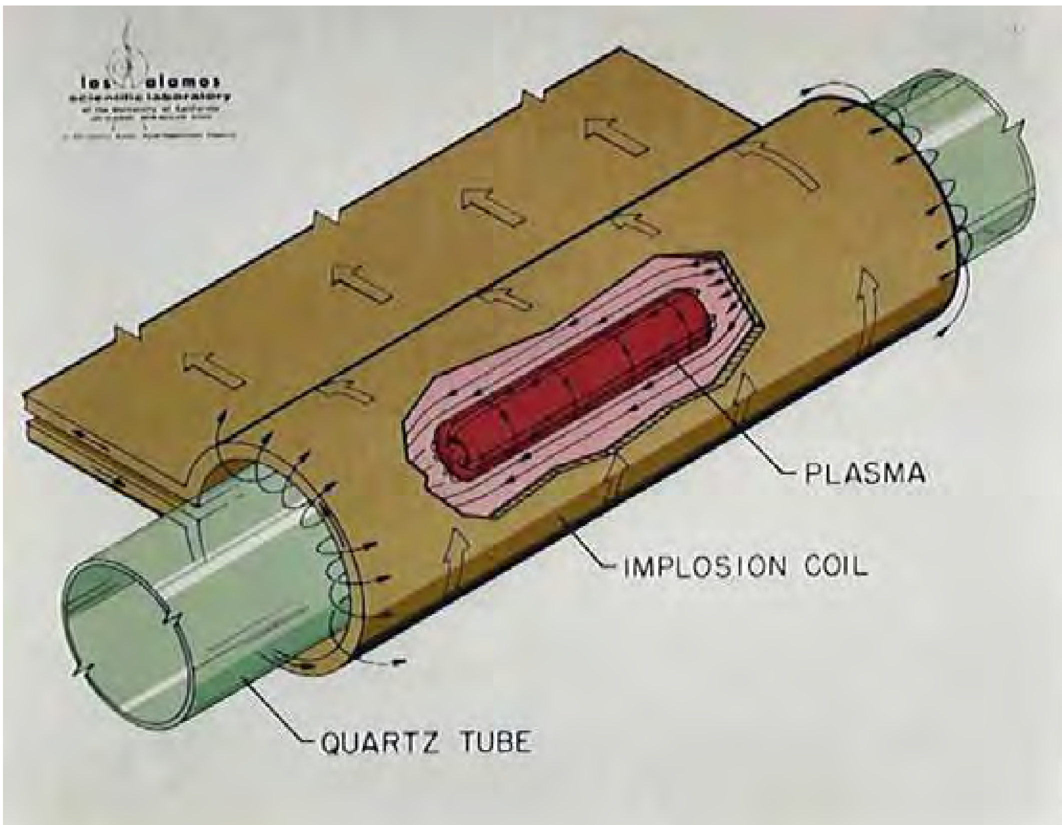
FRC



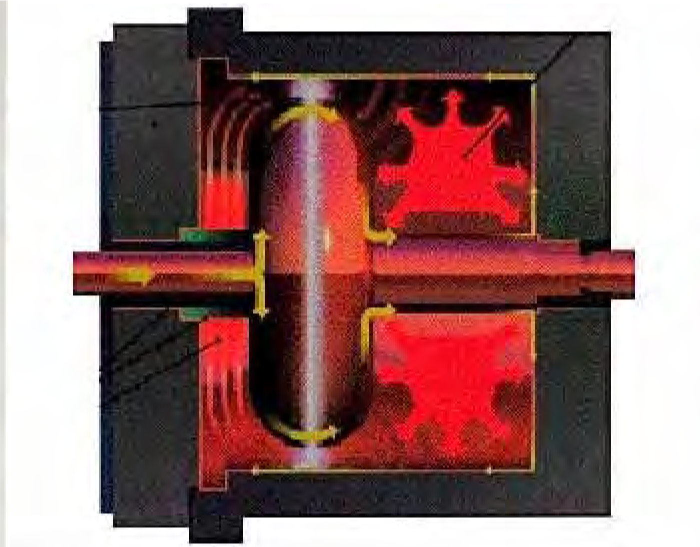
Self organized

In each case one investigates thermal diffusivity χ because $\tau_E = (\text{size})^2/\ \chi$

Possible MTF plasma targets

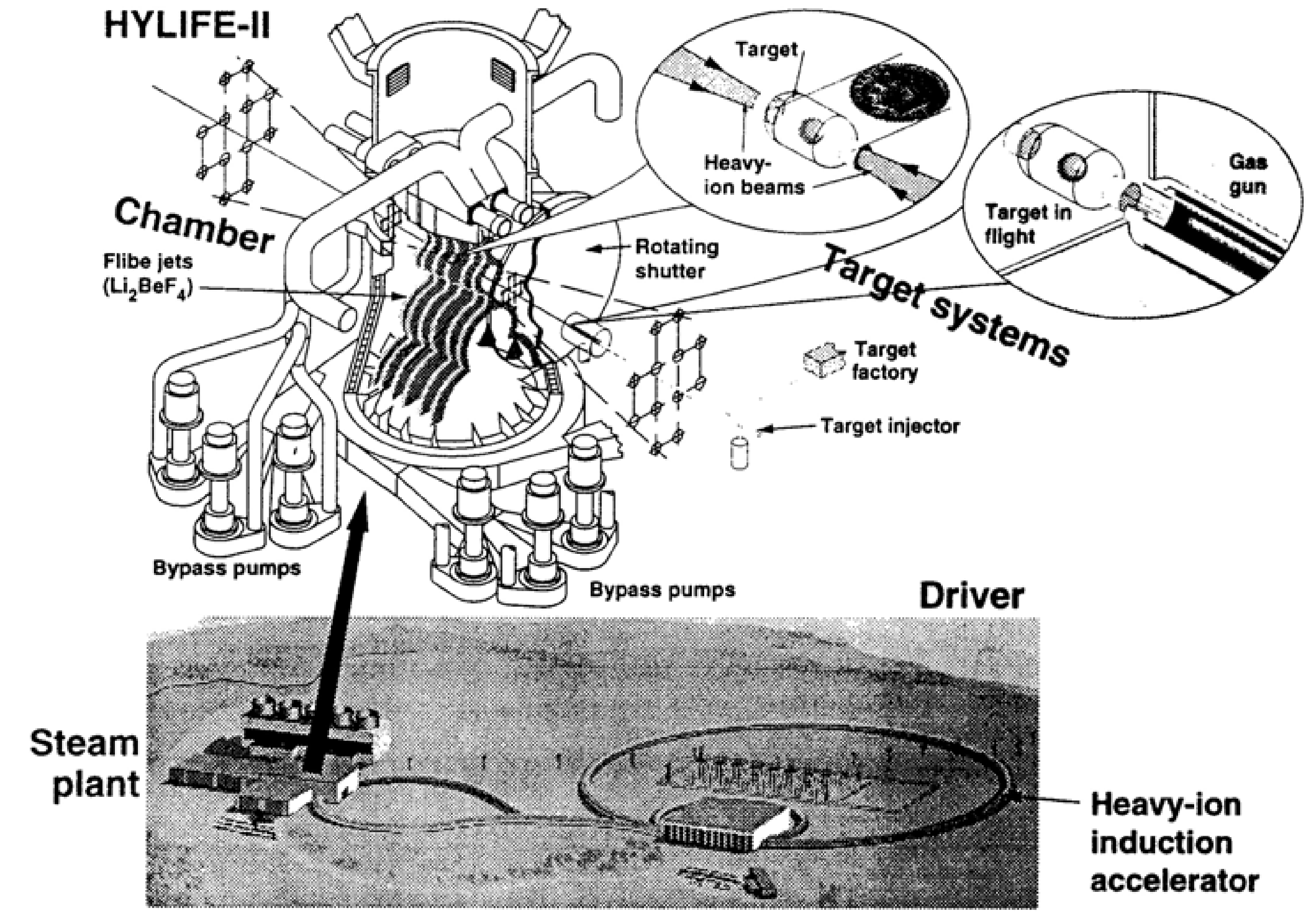


Field-Reversed Configuration



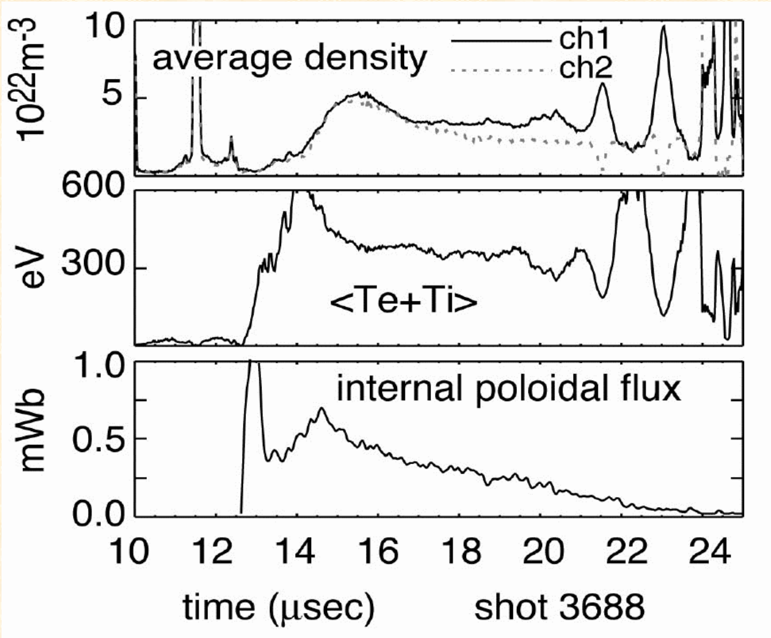
Russian MAGO

IFE power plant with stand-off driver



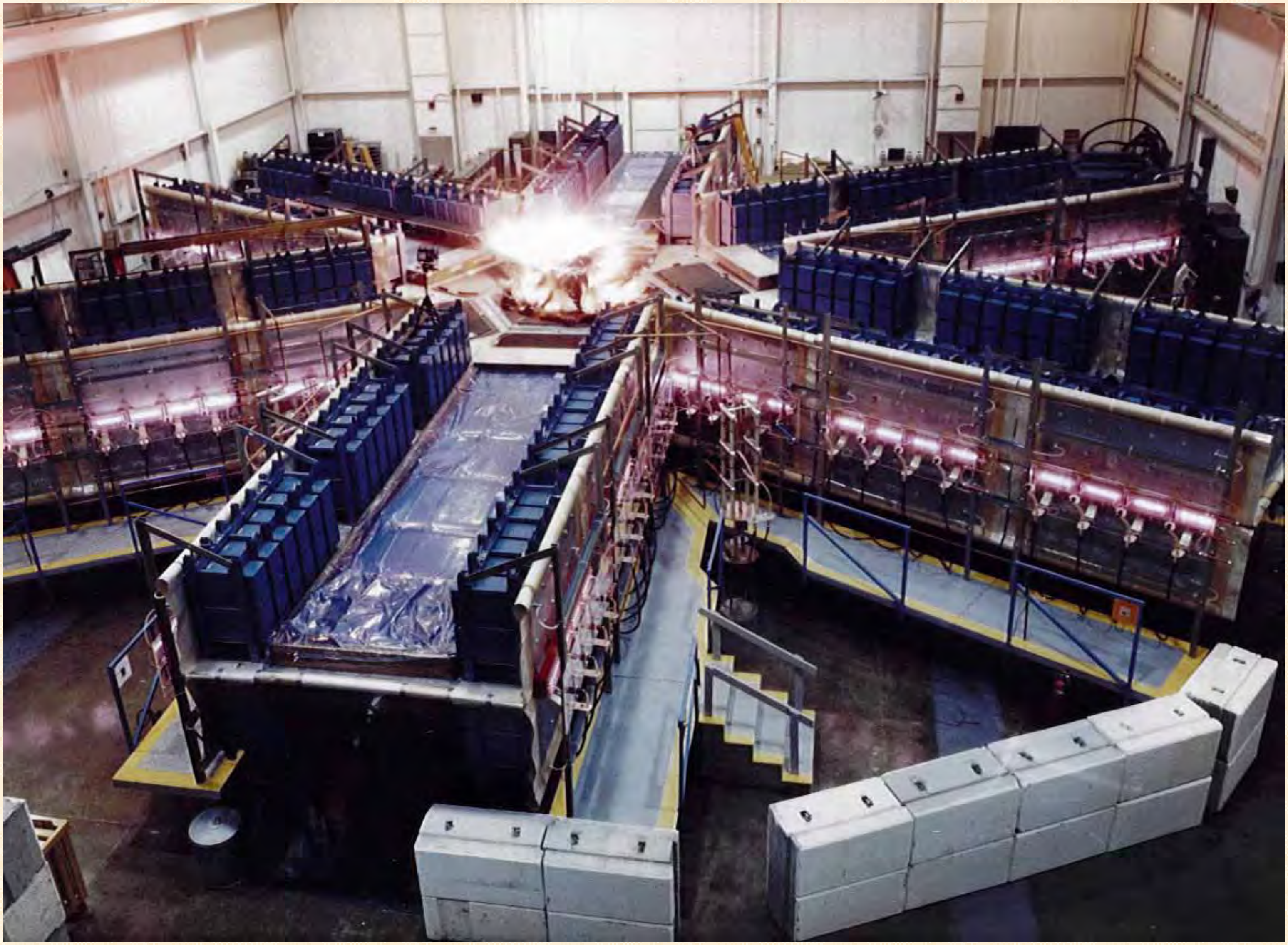
Liquid-jet protected fusion chambers for long lifetime, low cost, and low environmental impact

LANL has demonstrated high-density FRC formation

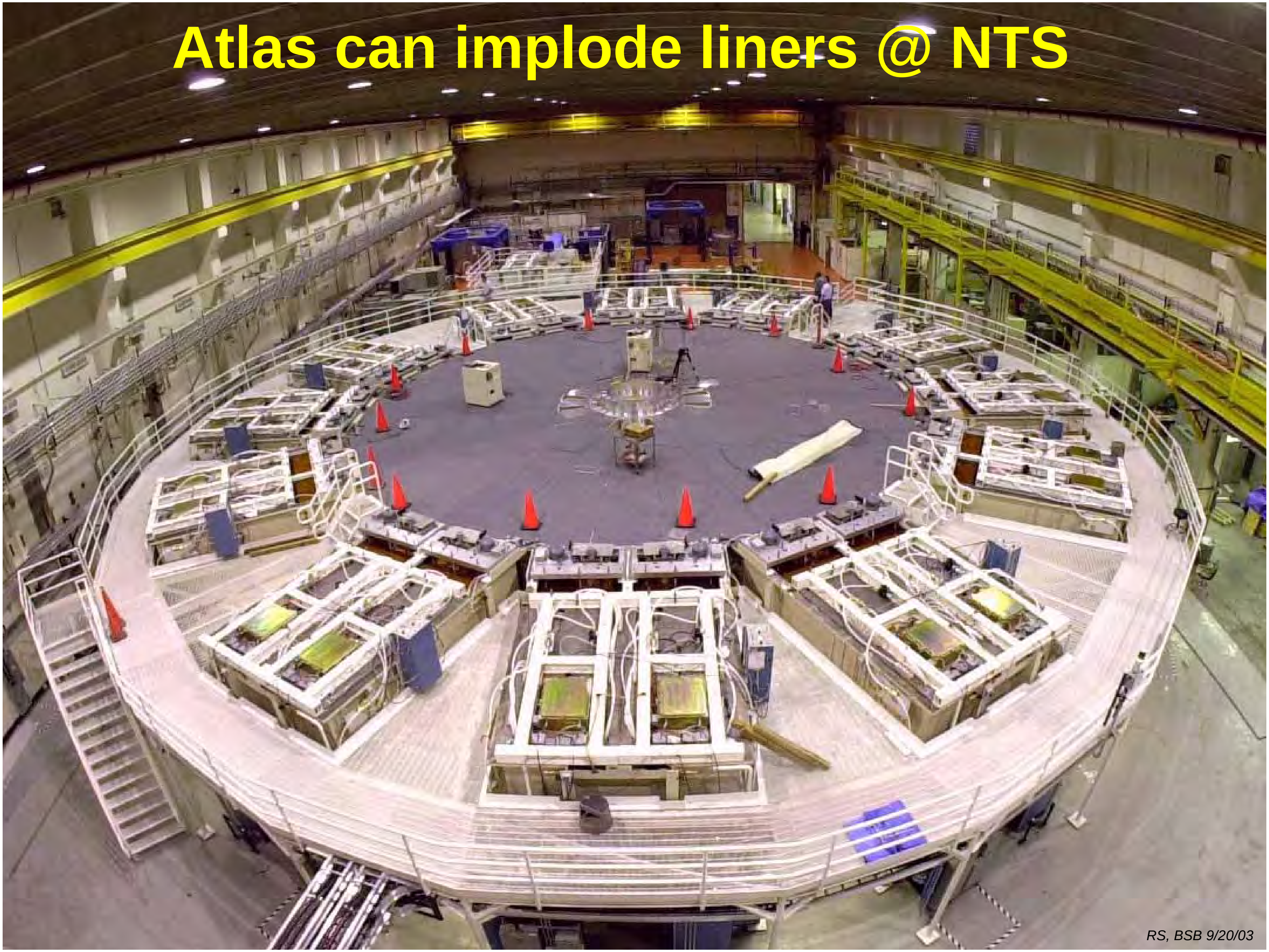


- Integrated liner-on-plasma experiments in next two years
- Goal to determine if liner flux compression can generate thermonuclear temperatures

Shiva Star at AFRL (Alb.)

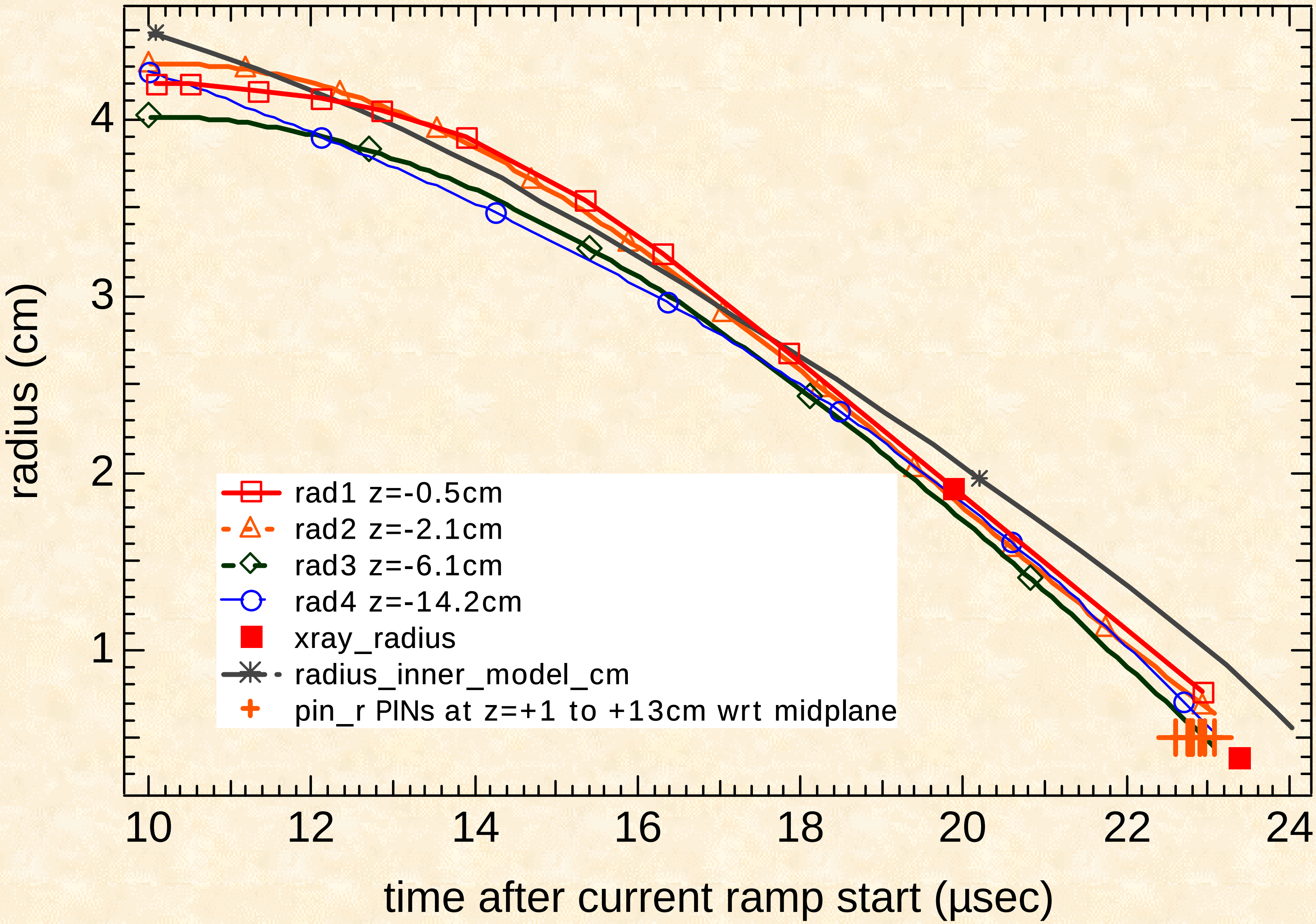


Atlas can implode liners @ NTS

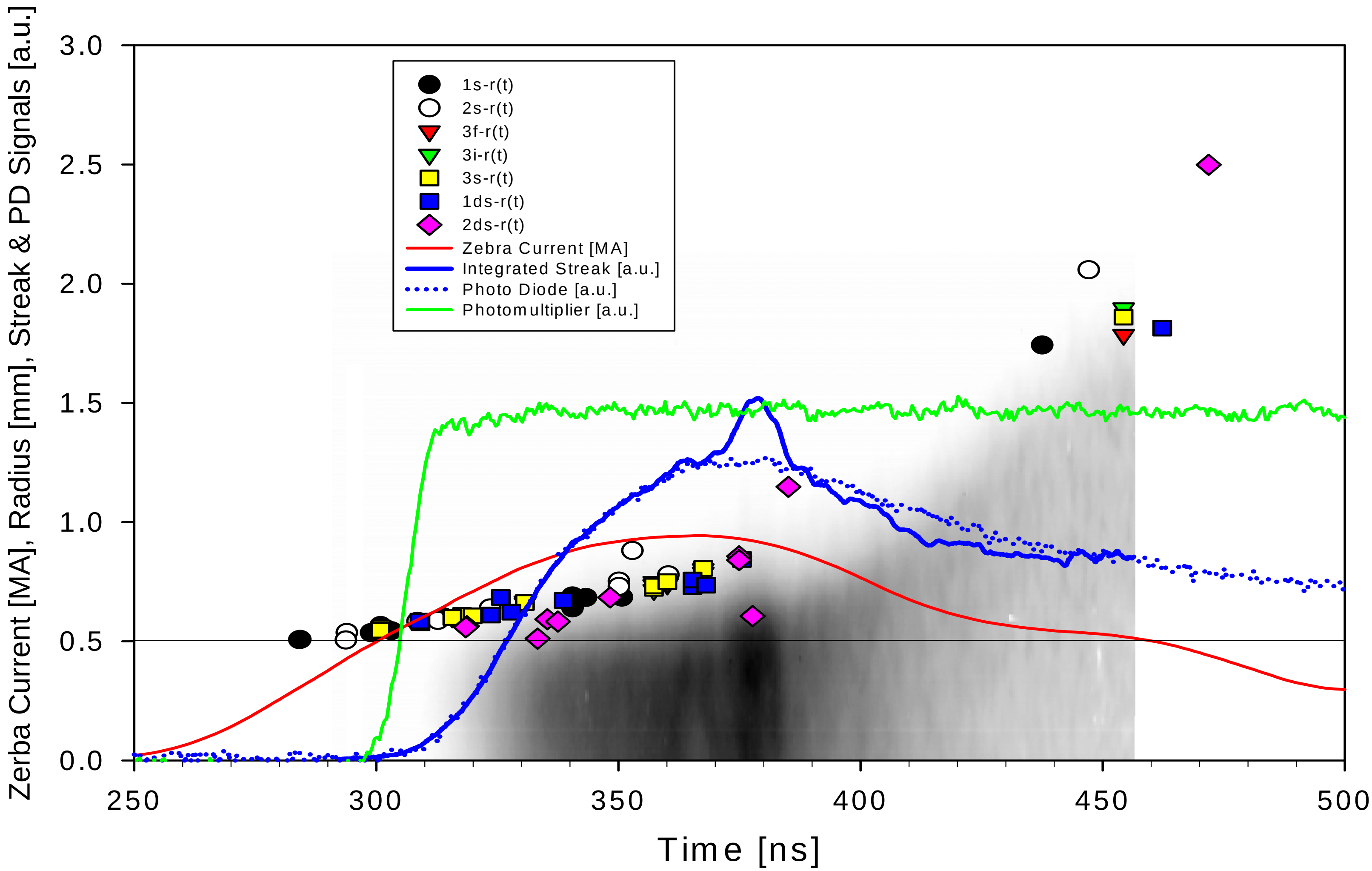


RS, BSB 9/20/03

Liner radius vs time

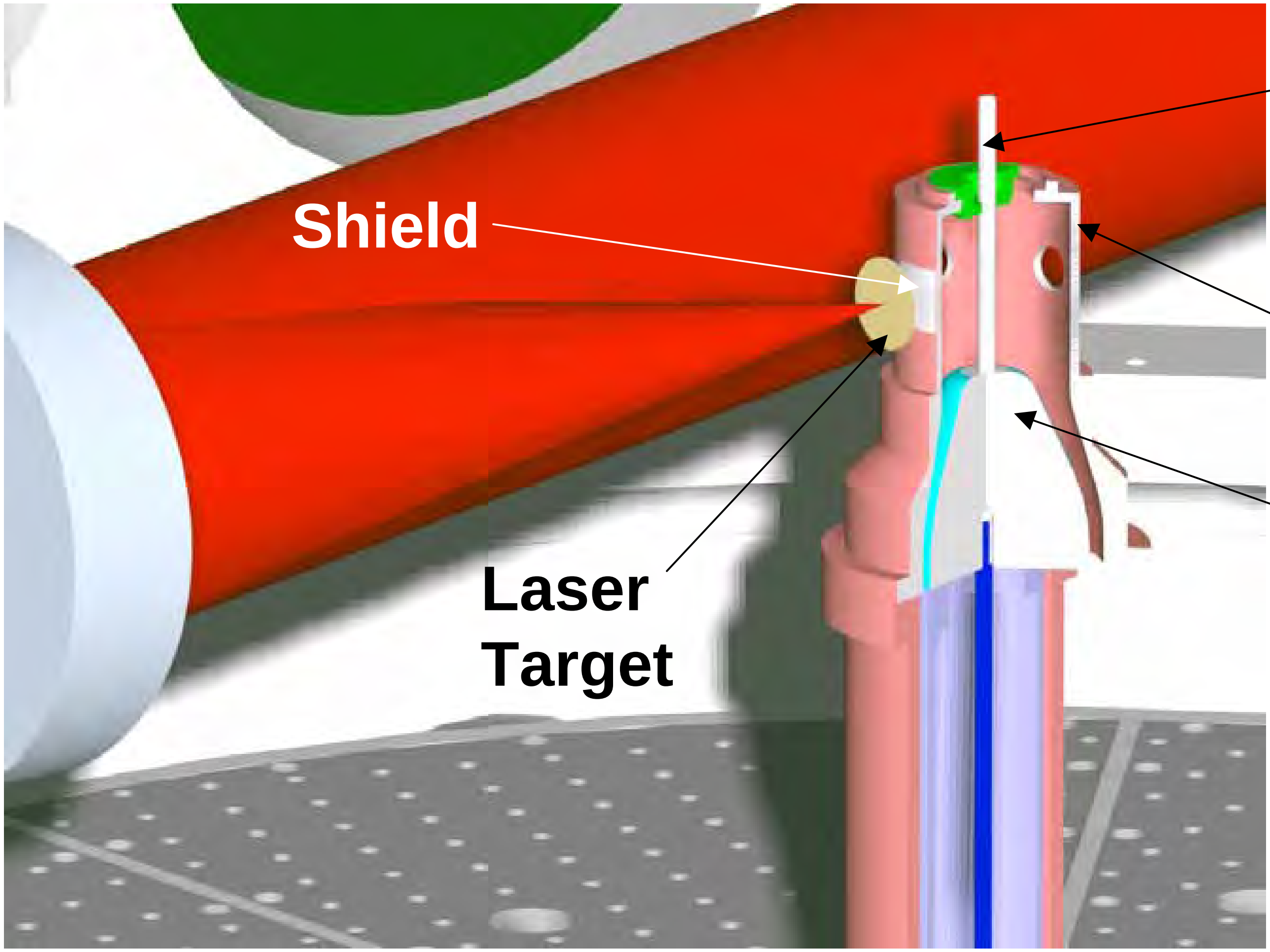


Streaked self-emission & laser shadowgrams show consistent plasma expansion



SF, BSB 2/09/07

Future possibility: Proton radiography of a liner implosion on Zebra



Tuesday Panel Discussion "What can/should we do to be prepared to take advantage of growing interest in and funding for IFE that could be triggered by a variety of events (e.g., successful ignition on NIF, increase concern about global climate change, increase interest in domestic energy sources, etc.)?" *

Opening statement by B. Grant Logan

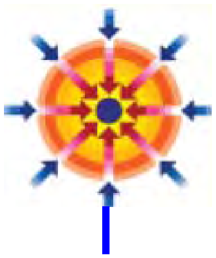
on behalf of the

Heavy Ion Fusion Science-Virtual National Laboratory**

Presented to:

IFE Science and Technology Strategic Planning Workshop

San Ramon, California
April 24-27, 2006



Heavy ion beams

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

** HIFS-VNL: A collaboration between Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory, USA.

We need to recognize the long-term challenge of IFE: address "What should/can we do" in both near term and long term contexts:

Near term:

- **Support campaigns for ignition and energy gain in the laboratory ASAP.**
- **Inform the public and its representatives in Congress how IFE could help address global warming and of opportunities for domestic fusion research for IFE using US facilities.**
- **Until ignition, make best use of limited funds: focus key research in areas that:**
  - **Build upon current knowledge base.**
  - **Address new research objectives that are relevant to both IFE as well as interesting new HEDP science.**
  - **Lead to potential improvement in IFE (e.g., higher gain, higher pulse rate, etc.).**
  - **Leverage existing assets for affordable experiments sooner.**

We need to recognize the long-term challenge of IFE: address "What should/can we do" …in the long term context:

We need to listen to critics of IFE and address their concerns! Below some "paraphrased" issues generic to several IFE approaches including HIF, → and a few ideas we could work on:

1. ***"I can't believe hitting targets on the fly with required precision in one shot, let alone at rep rate!"***
   → Research precision injection, tracking *and implosion symmetry* in multi-shot, on-the-fly, no-yield target experiments
2. ***"Fusion has never solved the first wall problem, and IFE is worst!"***
   → Research relevant-hydro-scale, thick-liquid-protected chamber experiments at hydro-scaled pulse rates relevant to IFE.
3. ***"Energy is cheap, precision targets are not!"***
   → Research mass production techniques for injectable targets that scale to IFE cost goal ~ < 1 mil per target per MJ yield.
4. ***"Why bother developing fusion when Gen4 fission will work sooner and longer!"***
   → Consider fissile fuel breeding if uranium costs grow too high.
   → T-lean targets with plasma direct conversion for winning CoE.

What can/should we do (*now*) to be prepared to take advantage of growing interest in and funding for IFE?

1) **Minimize ignition surprises (i.e., make sure the physics is right)**

2) **Develop the near term plan for post-ignition on the NIF (ignition may be the most certain event in the next 6-8 years)**

3) **Prioritize the IFE issues - *identify the scientific hard stops* - and tackle them with available resources (i.e., resource utilization)**

4) **Get the fast ignition story straight - is this part of #1, #2, #5 or an unnecessary diversion?**

5) **(Re)Establish a science program to attract/keep future generations**

6) **Establish/ensure a viable student pipeline (#4?)**

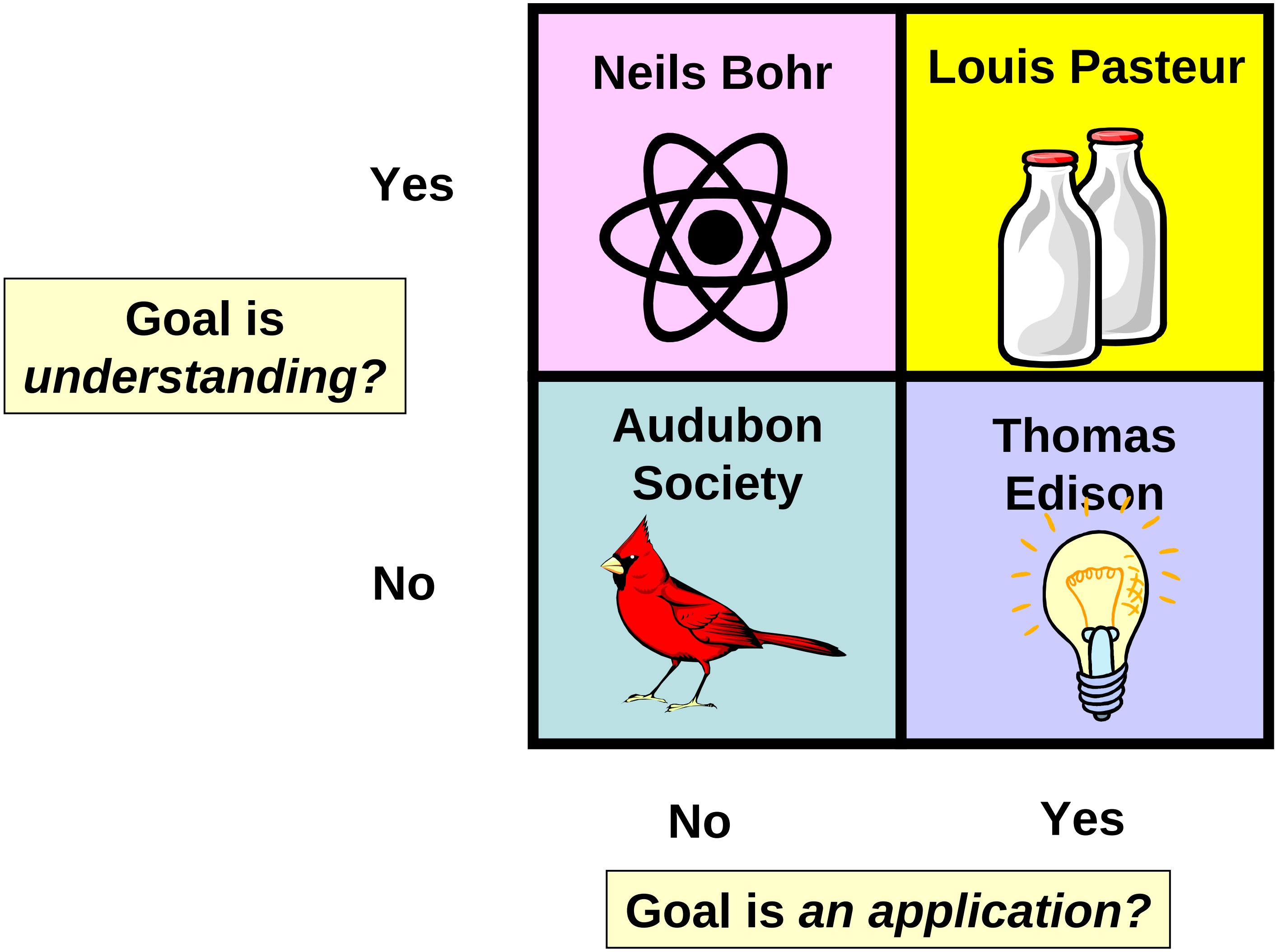
7) **Invest the time in communication/public awareness of the opportunities and potential of IFE**

Craig Sangster, UR-LLE

What can/should we do to be prepared to take advantage of growing interest in and funding for IFE that can be triggered by a variety of events….?

John Sethian, NRL

Answer: work in “Pasteur’s Quadrant”



adapted from "Pasteur's Quadrant", Donald E. Stokes, Brookings Press, 1997